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NASA Contractor Report 189181

Findings of a Review of Spacecraft Fire Safety Needs

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July 1992

Prepared for
Lewis Research Center
Under Contract NAS3-25975

NASA
National Aeronautics and
Space Administration

NASA CR 189181
UCLA ENG 92-19
April 1992

FINDINGS OF A REVIEW OF SPACECRAFT FIRE SAFETY NEEDS

G.E. Apostolakis, I. Catton, T. Paulos, K. Paxton, S. Jones

NASA IN-SPACE TECHNOLOGY EXPERIMENT PROGRAM

Contract: NAS3-25975
Risk-based Fire Safety Experiment

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CONTENTS

1.0 SUMMARY 1

2.0 INTRODUCTION 1

3.0 CURRENT SAFETY PRACTICES 2

4.0 PSA AND FIRE RISK IN HUMAN-CREW SPACECRAFT 3

5.0 COMBUSTION SCIENCE IN MICROGRAVITY 5

6.0 SMOKE 7

7.0 CONCLUSIONS 7

8.0 ACKNOWLEDGEMENT 8

9.0 REFERENCES 8

APPENDIX I: LIST OF WORKSHOP ATTENDEES 10

APPENDIX II: PRESENTATIONS 11

- APOSTOLAKIS, UCLA 12
- FRIEDMAN, NASA LEWIS 29
- CATTON AND ZUBER, UCLA 43
- FULLER, GARRICK, AND LIN, PLG 51
- RONNEY, PRINCETON 69
- ALTENKIRCH, MISSISSIPPI STATE 97
- KARYDAS AND DELICHATSIOS, FACTORY MUTUAL RESEARCH 111
- PAUPERAS, GARDNER, AND KIMZEY, McDONNELL DOUGLAS 129
- KIMZEY, CONSULTANT 153
- OHLEMILLER, NIST 157
- FERNANDEZ-PELLO, UC BERKELEY 177
- VEDHA-NAYAGAM, WYLE LABS 197

1.0 SUMMARY

This report summarizes the discussion from a review organized by the Risk-Based Fire Safety Experiment Project at the University of California, Los Angeles, and it includes the visual aids used in the presentations in an appendix. The review was a workshop intended to guide UCLA and NASA investigators on the state of knowledge and perceived needs in spacecraft fire safety and its risk management. The discussions and conclusions reinforce the viewpoint that Probabilistic Safety Assessment (PSA) methods, which are currently not used, would be of great value to the designs and operation of future human-crew spacecraft. The discussions also stressed the importance of understanding and testing smoldering as a likely fire scenario in space. A need for smoke damage modeling was also noted, since many fire-risk models ignore this mechanism and consider only heat damage.

2.0 INTRODUCTION

This report summarizes the presentations and findings of a review meeting organized by the Risk-Based Fire Safety Experiment Project at the University of California, Los Angeles. The project is sponsored by the NASA In-Space Technology Experiment Program (IN-STEP), and its principal goal is to develop and perform experiments based on Probabilistic Risk (or Safety) Assessment (PRA or PSA) needs that will be used in models to quantify fire risk in human-crew spacecraft.

The review was held at UCLA on October 31-November 1, 1991, and it was intended to guide the UCLA and NASA investigators on the state of knowledge and perceived needs in spacecraft fire safety and its risk management. The review was organized as a workshop with presentations on specified subjects and discussions by the participants during and following the presentations. The names and affiliations of attendees, including those who made formal presentations, are given in Appendix I.

The following sections briefly introduce the presentations of the review workshop, covering the topics of current safety practices, probabilistic risk assessments, combustion science in the spacecraft environment, and the specific hazard of smoke in spacecraft. The visual aids used in the presentations are in Appendix II.

3.0 CURRENT SAFETY PRACTICES

3.1 Design-to-Preclude Strategies

There are three necessary elements for fire: fuel, oxygen, and an ignition source. These three elements form what is known as the fire "triangle." Excluding one of the three legs of the triangle assures safety from fire. However, the complete removal of any element is impractical, if not impossible, in a human-crew spacecraft. Realizing that fire threats exist, designers may use the tool of Probabilistic Safety Assessment (PSA) to reduce risk to an acceptable level.

Several of the contractors working on spacecraft projects stressed the fact that a design-to-preclude strategy, that is, the a priori reduction of fire elements, is very important to their design approach. J. Pauperas of McDonnell-Douglas Space Systems Company in Huntington Beach, California, discussed many of the threats to orbital spacecraft and what steps are currently undertaken by engineers and designers to preclude catastrophes. Many risk consultants agree that, even with these risk-reduction strategies, there is a need for outside monitoring to counteract possible bias, intentional or unintentional, that arises where the designer must defend his or her own design. Some contractors already cooperate in this regard; however, several of the risk experts commented on the reluctance of other contractors to open themselves to outside monitoring.

R. Friedman of the NASA Lewis Research Center, in his presentation noted that, in addition to the fire elements already expected in current spacecraft, future missions will introduce greater fire risks through their complex configurations, varied crew activities, and scientific and commercial operations. Long-duration orbital missions also increase the probability of exposure to potential fire hazards.

3.2 Material Selection

Despite the design-to-preclude strategy, flammable materials are likely to be found in what is termed Government Furnished Equipment (GFE), according to H. Kimzey, private consultant to McDonnell-Douglas in Houston, Texas. For the Space Station *Freedom*, currently under design, these items will include paper, towels, food, and electrical equipment. In addition, the possibility arises that *Freedom* crew members will bring on board other items creating potential fire hazards, such as magazines or souvenirs, for the comforts of living during the long mission lengths.

NASA has methods and standards to assess material flammability through pass-fail tests, but testing of necessity must be conducted in a normal gravity environment. There is no proven correlation between normal-gravity and microgravity (near-zero gravity) flammability, and several scientists voiced concerns over material selection based solely on normal-gravity testing. According to T. Ohlemiller of the National Institute of Standards and Technology (NIST), NASA may want to consider supplemental tests, such as those with incident thermal radiation, for more realistic data. Ohlemiller's experiments have shown that materials that pass the NASA test criteria for resistance to flame spread may show appreciable flame-spread rates, if preheated. He also felt that the conventional NIST ignition-delay, heat release, and flame-spread tests provide a more complete, quantitative picture of flammability than the NASA pass-fail test.

For more information on these topics, see the presentations in Appendix II given by R. Friedman, H. Kimzey, T. Ohlemiller, and J. Pauperas.

4.0 PSA AND FIRE RISK IN HUMAN-CREW SPACECRAFT

The complexity of engineering systems and the requirements for reliable and safe operations have created the need for the development of models that accurately represent these systems. The occurrence of major accidents (e.g., Bhopal, Chernobyl, Challenger) has focused the attention of the public on the safety of these facilities and has accelerated the development and use of these models. It is clear that major failure events of interest are rare and any decision-making process that involves such events must include the large uncertainties that are associated with their occurrence.

Although the established fire-risk concepts and methodologies have been developed for industrial and nuclear power plants, they can also be applied to human-crew spacecraft. A PSA of fires may be described as a four-step process.[1] The first step is identify "critical locations." The second step is to assess the frequency of fires. The third step is to determine the fraction of fires which damages critical components. The last step is to determine the conditional frequency of severe consequences, given that damage to critical components has occurred.

Accident scenarios arise from the identification of "critical locations." In nuclear power plants, these are areas where a fire can disable redundant components. In *Freedom*, any fire will be a major concern. However, some locations will be more important than others. For example, any region of *Freedom* where a fire could disable a major system is much more important than a region where a fire could destroy a light panel. Much work has already been done in determining accident scenarios. Most fire scenarios that have been examined are based on incidents originating within a closed compartment termed a "rack," which is essentially a wall drawer.[2] The occupied *Freedom* volumes, or modules, will be constructed of banks of many racks surrounding the central core volume on four sides. Most of the racks will contain electrical equipment; many may also contain flammable solids or fluids.

To assess the fraction of fires which damage critical components, the competition between fire growth and suppression must be determined. Suppression efforts include both the time to detection and the actual suppression time. This is not an easy determination. Much work in terrestrial applications has been done in this area over the years; and, for an actual analysis (usually for nuclear power plants), the growth part is usually determined through the use of computer models, such a COMPBRN IIIe.[3]

Space Station *Freedom* represents a tremendous effort in terms of dollars and labor. Fire on board the space station is the threat with potentially the most catastrophic consequences.[4] Fire threatens the occupants not only with the obvious dangers of heat, toxic gases and structural failure but also in other, more subtle ways. Trace constituents generated by both combustion and extinguishment can contaminate the atmosphere and corrode electrical and sensitive components over periods of time.[5,6] Repeated false alarms due to oversensitive detectors can disrupt the activity schedules and reduce the crew's confidence in the protective systems.

In the past, missions of several weeks were deemed as long-term, but, as R. Friedman pointed out, *Freedom* has a planned 30-year or greater lifetime. Due to this longer service life, and the increased stresses from greater mission responsibilities and longer crew duty periods, plus new and increased quantities of onboard materials and processes, the value of PSA should be apparent. W. Fuller of PLG, Inc. in Newport Beach, California stated that the power of PSA lies in the ability to analyze all conceivable accident sequences and prioritize their contributions to risk. Even though PSA is design specific, it can be used in an evolutionary process where analysts cooperate with designers throughout the development of the project. The result is an improved design, without the need for retrofit or redesign. Also, through this interaction, designers become more risk aware in their designs. He also stated that for *Freedom*, the Japanese Experiment Module (JEM) incorporates a complete PSA, but the U.S. modules include only qualitative safety assessments in their planning.

Although this review centered solely on the fire threat, it should be noted that other threats also exist. For example, explosion, collision, radiation and tumbling are additional threats that can also have serious consequences.[7,8] M. Vedha-Nayagam of Wyle Laboratories in Huntsville, Alabama stated that, even if the fire is the sole objective of our efforts, its threat is multifaceted. The emphasis must be focused on risk minimization, not just the understanding of some aspects of combustion in microgravity. Due to testing time constraints, microgravity experiments for fire safety need to be designed to obtain the most information possible from each trial, with appropriate test matrices developed in advance.

For more information on these topics, see the presentation in Appendix II given by G. Apostolakis, R. Friedman, W. Fuller, J. Pauperas, and M. Vedha-Nayagam.

5.0 COMBUSTION SCIENCE IN MICROGRAVITY

Several presentations dealt strictly with combustion science in microgravity. Since a meaningful risk assessment must rely on understanding the physical phenomena involved, there were many ideas and concepts mentioned that could be utilized in a risk-based approach.

R. Altenkirch of the Mississippi State University stated that, due to the absence of gravity and the accompanying buoyancy effects, the mechanisms of combustion are driven by transport other than natural convection, most notably radiation, and even simple heat-balance analyses must include radiation. Conduction may also be important, if thermally thick fuels are tested.

T. Ohlemiller of NIST presented some results that showed the two ways in which radiation is important. First, it can act as a feedback mechanism, so that the heat of the flame is directed back onto itself, driving the reaction faster. It can also preheat the fuel ahead of the flame, which can have a major impact on how the combustion process is driven.

The smoldering hazard was discussed by C. Fernandez-Pello of the University of California at Berkeley. Although smoldering is mostly a fuel-controlled process in microgravity, it can represent a major hazard. Smoldering can even occur in a vacuum, if oxygen is retained in the fuel matrix. Several scientists expressed skepticism on whether any useful results can be obtained in the available short-term test bed facilities. For example, airplane platforms can supply a maximum of twenty-five seconds of sustained microgravity. Smoldering processes in microgravity will need to be examined on the order of minutes to obtain useful results, and eventually these tests will have to be conducted on the Shuttle or *Freedom.*

P. Ronney of Princeton University discussed the use of extinguishing agents. Innovative agents, such helium and sulfur hexafluoride (SF_6), have been found to have excellent extinguishing properties. These evaluations are based on extinguishment limits observed in tests with premixed atmospheres diluted by the agent. Long-duration tests with the agent introduced to extinguish an established fire have not been performed.

T. Steinberg of the White Sands Test Facility in White Sands, New Mexico discussed his work on the combustion of metals in microgravity. These experiments are performed in pure oxygen environments at extremely high pressures (approximately 7 MPa or 1000 psi). One interesting note here was the ensuing discussion on calculating heat release. From precise temperature and pressure measurements, both the heat release and oxygen depletion can be calculated using simple thermodynamic relationships. This approach seems feasible for quiescent environments, but it may prove difficult to apply to flow-type experiments due to the inaccuracies that would be encountered in measuring pressure.

One final topic mentioned during the discussion period by M. Delichatsios of the Factory Mutual Research Corporation in Norwood, Massachusetts is it may be possible to use key flammability properties, such as surface temperature or heat of combustion, to predict the microgravity flame-spread rate. If such relationships could be discovered, material flammability properties could be incorporated into models that predict flame spread rates.

For more information on these topics, see the presentations in Appendix II given by R. Altenkirch, C. Fernandez-Pello, T. Ohlemiller, and P. Ronney. T. Steinberg's presentation was on slides, and no overheads were available. M. Delichatsios' viewgraphs are grouped with those of D. Karydas.

6.0 SMOKE

Many computer models for fire attribute damage solely to heat release and ignore smoke generation and its damaging effects. However, according to M. Delichatsios and D. Karydas, also from FMRC in Norwood, Massachusetts, smoke can be both highly toxic and highly corrosive. Recent work has shown that not only should smoke effects be considered in fire models, but, in fact, smoke may be more damaging than heat. Several important characteristics of smoke are particle composition, particle size, particle density, particle charge, and particle morphology. These characteristics, along with velocity distributions, can be incorporated into computer codes (e.g., MAEROS 2) to determine the damaging effects of smoke.[9]

The smoke characteristics need to be supplemented with the smoke deposition rates. It is hoped that this information could be used to determine a critical deposition rate. The rate would directly relate to a probabilistic damage model for a component, from which a damage distribution could be assessed. This type of damage model may not be necessarily accurate, but it offers a more realistic approach than a model based exclusively on heat release.

For more information on these topics, see the presentations in Appendix II given by D. Karydas and M. Delichatsios (one set).

7.0 CONCLUSIONS

Some participants at the review workshop expressed their strong belief that an extensive Probabilistic Safety Assessment (PSA) of the Space Station *Freedom* needs to be conducted. Because of the effort in dollars and labor that will be spent on *Freedom*, all safety precautions, including the use of PSA, should be used to minimize threats. Although several scientists in the combustion field expressed concern over the use of PSA (primarily over the unavailability of sufficient information to perform a defensible PSA), most attendees, particularly those in the spacecraft safety and risk fields, agreed that this approach is very promising. Through the identification of the major hazards, a first step can be taken into quantifying the fire risk of human-crew spacecraft.

Smoldering is a likely spacecraft fire scenario, producing toxic gases, ash, and other undesirable products. A major question discussed by the participants is whether or not smoldering tests can be performed in a ground-based microgravity environment. Obviously, the drop towers do not provide the time needed; and, even with the use of airplane facilities, there will not be enough time in sustained microgravity to obtain useable results. In airplanes, continued parabolic flight paths can be flown, giving longer periods alternating between normal (actually increased) gravity and reduced gravity. However, there is concern that, during the gravity phase of these flights, the smoldering experiment may flash over, ending the smoldering test. Thus, full and complete smoldering tests will most likely have to performed in a space environment.

Another question posed was that of relating smoke production to smoke damage. In terrestrial fires, heat is normally treated as the contributing factor for damage. Many computer models, which deal with fire growth to damage, do not even consider smoke. However, recent work done in the field has shown the importance of smoke in fire scenarios.

Finally, given the success of the workshop in bringing about useful discussion and idea exchange among specialists in the several fields involved, participants expressed the desire for continued encounters of this nature at regular intervals in the future as the studies progress.

8.0 ACKNOWLEDGEMENT

The workshop documented in this report was sponsored by Contract NAS3-25975 from the NASA In-Space Technology Experiment Program (IN-STEP). We would like to thank the NASA project monitor and technical contact, Mr. Robert Friedman, for the assistance and guidance provided in the organization of the workshop and the overall orientation of this project. Special thanks are extended to all workshop participants and attendees who have shared with us ideas and discussions.

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8. W.R. Fuller, and M.W. Halverson, "Space Station *Freedom* Program Risk Model Control Document," PLG, Inc., Newport Beach, CA, June 1989.

9. F. Gelbard, "Multicomponent Aerosol Code MAEROS 2," Sandia National Laboratories, Containment Modelling Division, 6429, Albuquerque, NM, 1989.

APPENDIX I: LIST OF WORKSHOP ATTENDEES

NAME	COMPANY	TELEPHONE & FAX
Acosta, Gabriela	AiResearch	310/512-2850
Altenkirch, Bob	MSU	601/325-2270 & 601-325-8573
Apostolakis, George	UCLA	310/825-1300 & 310-206-2302
Blair, Harvey	AiResearch	602/469-5739 & 602-469-5975
Catton, Ivan	UCLA	310/825-5320 & 310-206-4830
Chapman, Dee	Boeing	205/961-4594
Delichatsios, Michael	FMRC	617/762-4300 x2777
Fendell, Frank	TRW	310/812-0327
Fernandez-Pello, Carlos	UC Berkeley	510/642-6554
Friedman, Robert	NASA Lewis	216/433-5697 & 216-433-8660
Fuller, Bill	PLG, Inc.	714/833-2020 & 714-833-2085
Gard, Melissa	NASA/MSFC	205/544-4337 & 205-544-5874
Gardner, Andrea	McDonnell Douglas	714/893-3311 x70481
Guarro, Sergio	The Aerospace Corp.	310/336-8610 & 310-336-5581
Hu, Ray	AiResearch	310/512-2546
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Kourtides, Demetrios	NASA Ames	415/604-4784
Loria, John	NASA Headquarters	202/453-2838
Ohlemiller, Tom	NIST	301/975-6481
Paulos, Todd	UCLA	310/825-2040
Pauperas, John	MDSSC-H.B.	714/896-3311 x71517
Paxton, Kevin	UCLA	310/825-2040
Ronney, Paul	Princeton Univ.	609/258-5278 & 609-258-6109
Schaff, Carolyn	Barios Technology/USC	713/283-8109
Steinberg, Ted	LESC-NASA-WSTF	505/524-5680
Thomas, Emory	Brunswick	714/546-8400 x6128
Urban, David	NASA Lewis	216/433-2835
Vedha-Nayagam, M.	Wyle Labs/Huntsville, AL	205/837-4411 & 205-830-2689

APPENDIX II: PRESENTATIONS

"Fire Risk Assessment Methodology," **George Apostolakis**, UCLA

"NASA Spacecraft Fire-Safety Program: Background and Issues," **Robert Friedman**, NASA Lewis

"An Integrated Structure for Technical Issue Resolution," **Ivan Catton**, UCLA and **N. Zuber**, NRC

"Space Station Freedom Quantitative Risk Analysis," **William Fuller**, **B.J.Garrick**, and **J.C.Lin**, PLG. Inc.

"Effects of Ambient Atmosphere on Flame Spread and Extinguishment," **Paul Ronney**, **Y. Zhang**, and **E.V. Roegner**, Princeton University

"A Study of the Mechanisms of Gas-Phase Flames Spreading Over Solid Fuels in Quiescent Environments," **Robert Altenkirch**, Mississippi State University

"Methodology for Fire and Smoke Hazard," **Dimitrios Karydas** and **Michael Delichatsios**, Factory Mutual Research Corporation

"Fire Hazard Control and Risk Minimization on Space Programs," **John Pauperas**, **A. Gardner**, and **H. Kimzey**, McDonnell Douglas Space Systems Company

"The Design of Spacecraft, Including Material Selection, and Its Role in Accidental Fire," **H. Kimzey**, Consultation

"A Perspective on the NASA Flammability Screening Test," **Tom Ohlemiller**, National Institute of Standards and Technology

"Gravity Effects on Smoldering of Polyurethane Foam," **Carlos Fernandez-Pello**, University of California, Berkeley

"Flight Hardware Requirements for Spacecraft Fire Safety Investigations: Current Status and Future Requirements," **M. Vedha-Nayagam**, Wyle Laboratories

FIRE RISK ASSESSMENT METHODOLOGY

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TABLE 1. Summary of the case study decomposition results

Zone Designator/ Scenario	Percentile	Frequency, Events Per Year		λ_j	$Q_{d\|j}$	$Q_{CD\|d,j}$	$Q_{R\|CD,d,j}$
		λ_{CD}*	λ_R**				
1. Fire Under Cables Damaging Switch-Gears and Power Cables to Component Cooling and Safety Injection Pumps	5th	4.6-8	4.6-8	1.1-7	0.32		
	50th	7.9-6	7.9-6	1.3-5	0.62		
	95th	4.2-4	4.2-4	3.7-4	0.90		
	Mean	7.1-5	7.1-5	1.2-4	0.62	1.0	1.0
2. Fire in the Aisle Damaging Power Cables to Component Cooling and Safety Injection Pumps	5th	5.5-8	5.5-8	1.2-7	0.20		
	50th	4.7-6	4.7-6	8.4-6	0.55		
	95th	1.0-4	1.0-4	1.6-4	0.87		
	Mean	2.4-5	2.4-5	4.2-5	0.57	1.0	1.0
3. Fire on the Floor Damaging Control Cables 10 Feet Above the Floor and Failing All Control and Instrumentation Capability	5th	3.0-10	<1.0-10	5.3-7	0.12	2.5-4	0.02
	50th	7.3-8	7.3-9	3.3-5	0.45	5.0-3	0.1
	95th	3.3-6	5.9-7	5.0-4	0.80	1.0-1	0.5
	Mean	1.9-6	3.0-7	1.5-4	0.48	2.6-2	0.16

*Core damage frequency: $\lambda_{CD} = \lambda_j Q_{d|j} Q_{CD|d,j}$.

**Radionuclude release frequency: $\lambda_R = \lambda_j Q_{d|j} Q_{CD|d,j} Q_{R|CD,d,j}$.

NOTE: Exponential notation is indicated in abbreviated form; i.e., 4.6-8 = 4.6×10^{-8}.

Summary of the Case Study Decomposition Results

Zone Designator/ Scenario	Percentile	Core Damage Frequency, Events per year λ_{CD}
1. Fire under cables damaging switchgears and power cables to component cooling and safety injection pumps.	5th 50th 95th Mean	4.6-8 7.9-6 4.2-4 7.1-5
2. Fire in the aisle damaging power cables to component cooling and safety injection pumps.	5th 50th 95th Mean	5.5-8 4.7-6 1.0-4 2.4-5
3. Fire on the floor damaging control cables 10 feet above the floor and failing all control and instrumentation capability.	5th 50th 95th Mean	3.0-10 7.3-8 3.3-6 1.9-6

NOTE: Exponential notation is indicated in abbreviated form; i.e., 4.8-8 = 4.8×10^{-8}.

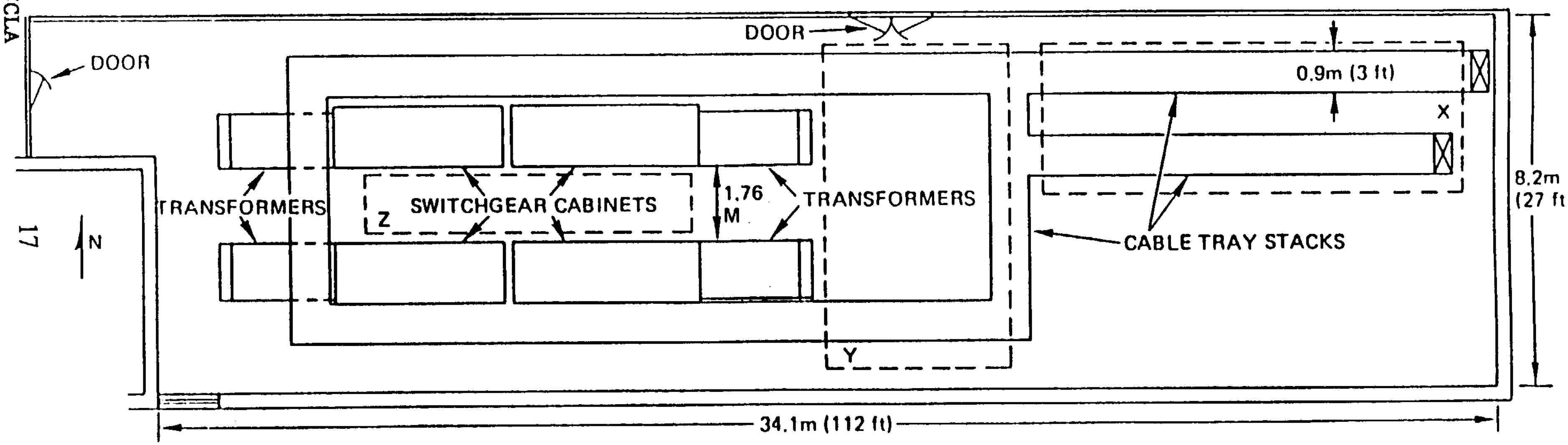
Summary of the Case Study Final Results

Option	Description	Percentile	λ_{CD} Events Per Year	Reduction Factor
0	Base Case	5th	2.2×10^{-6}	
		50th	3.0×10^{-5}	
		95th	1.1×10^{-3}	
		Mean	1.0×10^{-4}	1.0
1	Self-Contained Charging Pump	5th	1.6×10^{-6}	
		50th	8.8×10^{-6}	
		95th	9.9×10^{-5}	
		Mean	1.9×10^{-5}	5.3
2	Alternate Power Source	5th	1.7×10^{-6}	
		50th	7.1×10^{-6}	
		95th	4.8×10^{-5}	
		Mean	1.4×10^{-5}	7.1

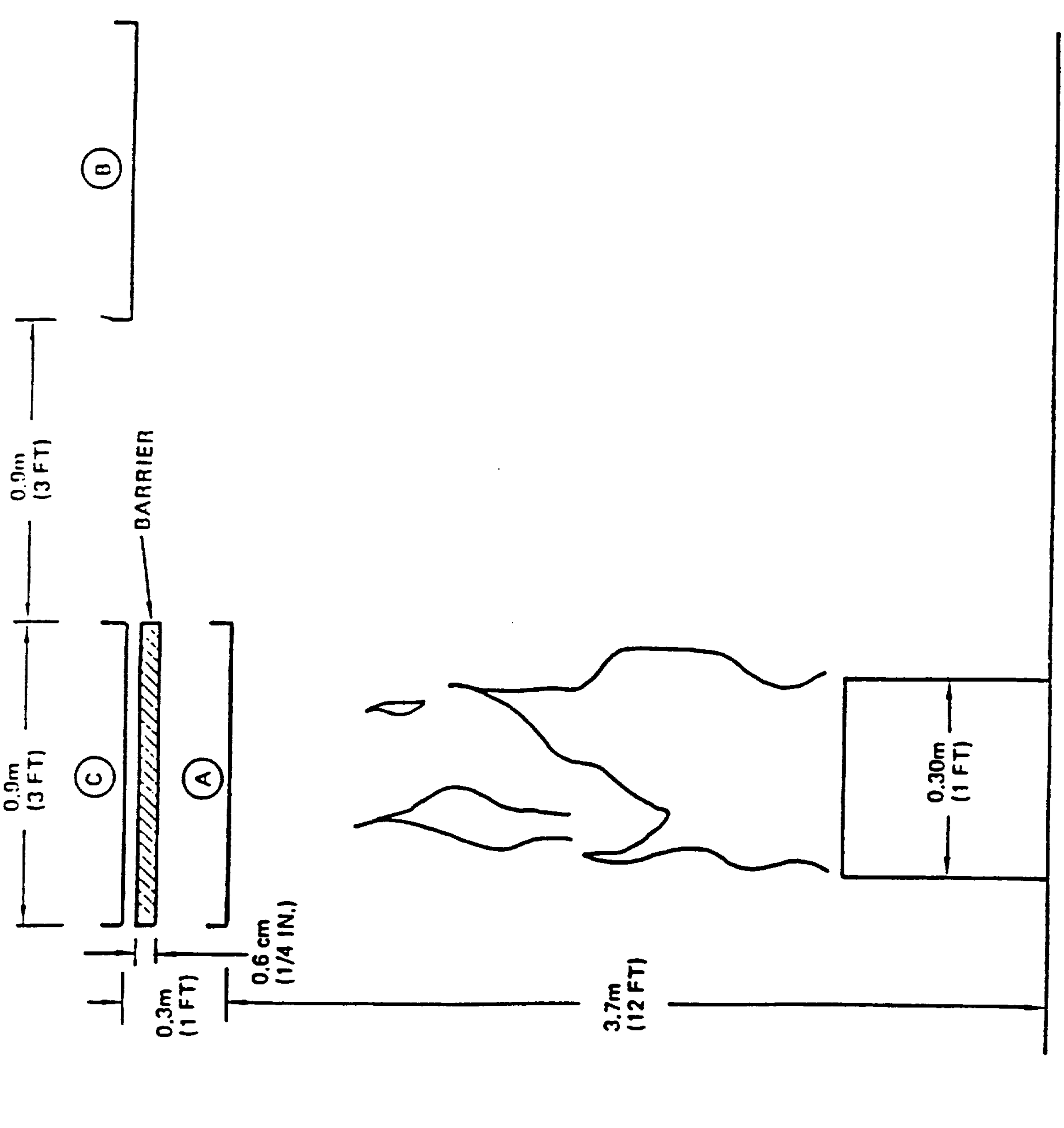
FIRE ANALYSIS METHODOLOGY

1. CRITICAL LOCATIONS
2. FREQUENCY OF FIRES (DATA, SPECIFIC LOCATIONS, LARGE FIRES)
3. GROWTH MODELS (VERTICAL/HORIZONTAL PROPAGATION, CABINETS, PARAMETER AND MODELING UNCERTAINTIES)
4. SUPPRESSION MODELS
5. COMPETITION BETWEEN GROWTH AND SUPPRESSION
6. EVENT TREES (ACCIDENT SEQUENCES, FAILURES INDEPENDENT OF FIRES)

G. Apostolakis, UCLA

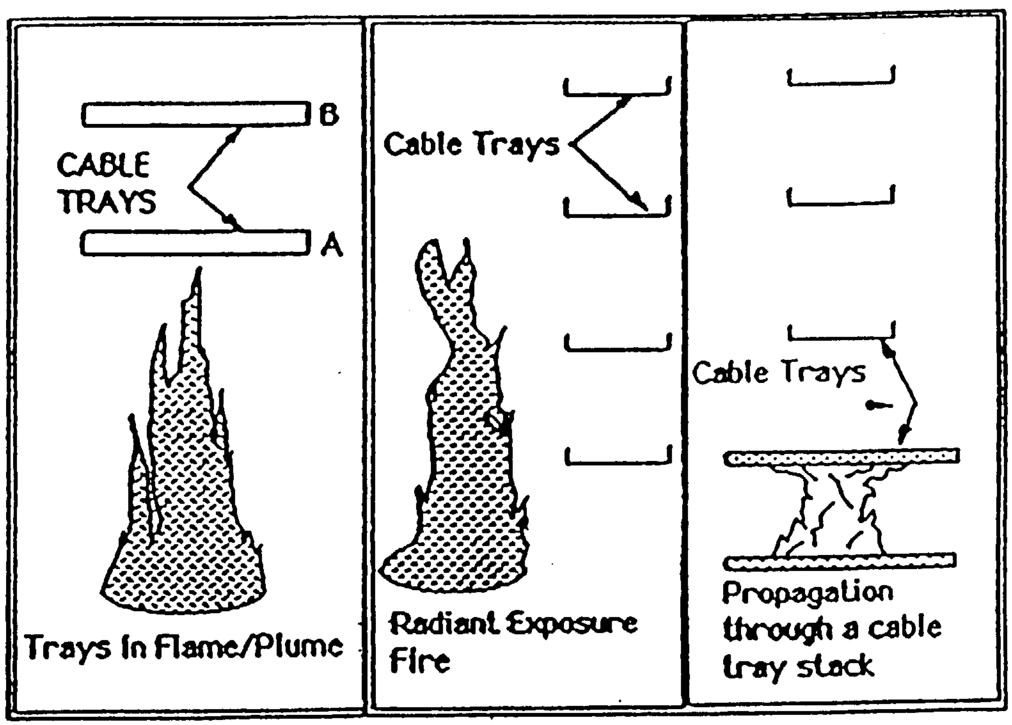


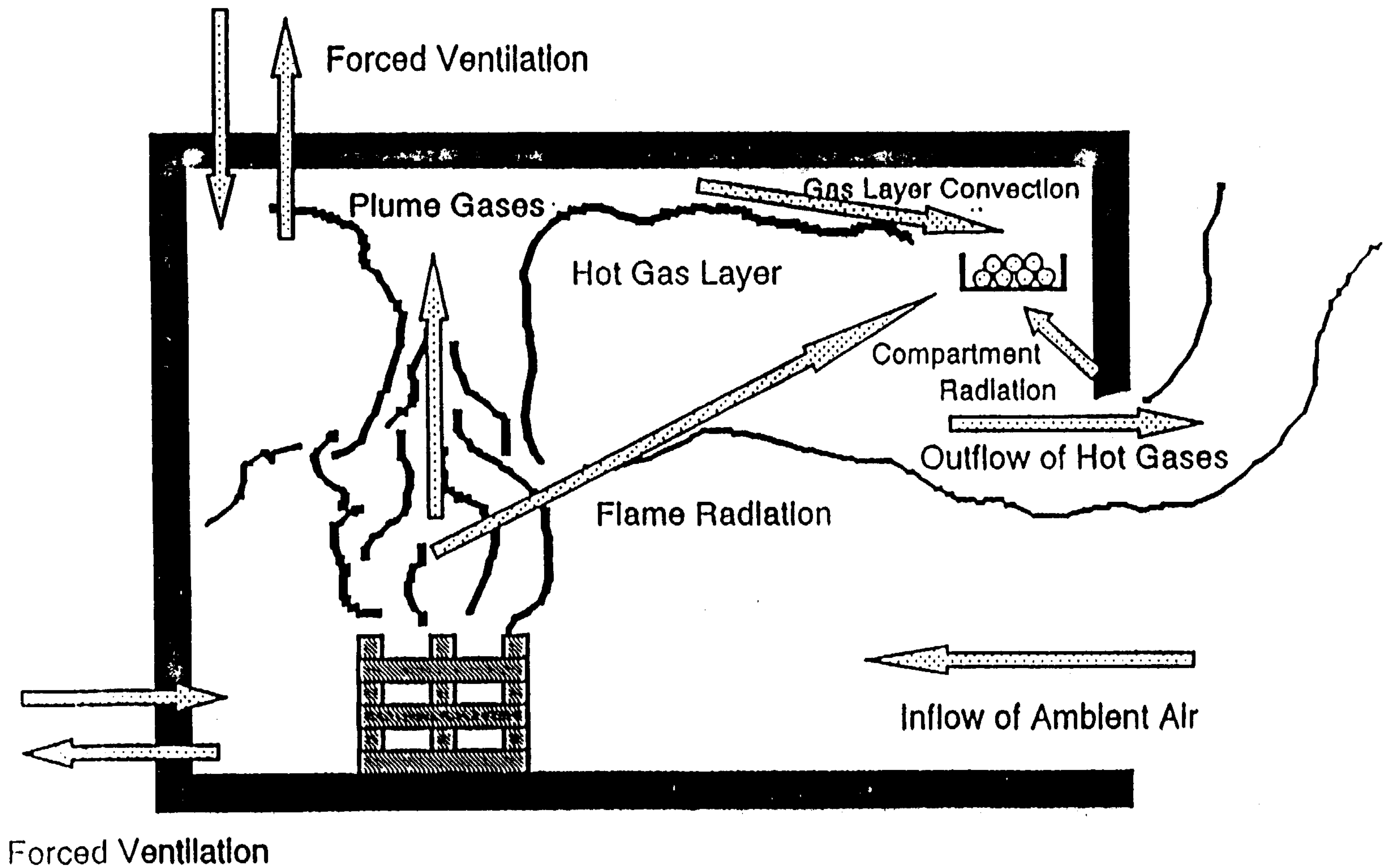
TOP VIEW OF A SWITCHGEAR ROOM



ELEVATED CABLE TRAY STACKS AT THE EASTERN PART OF THE SWITCHGEAR ROOM

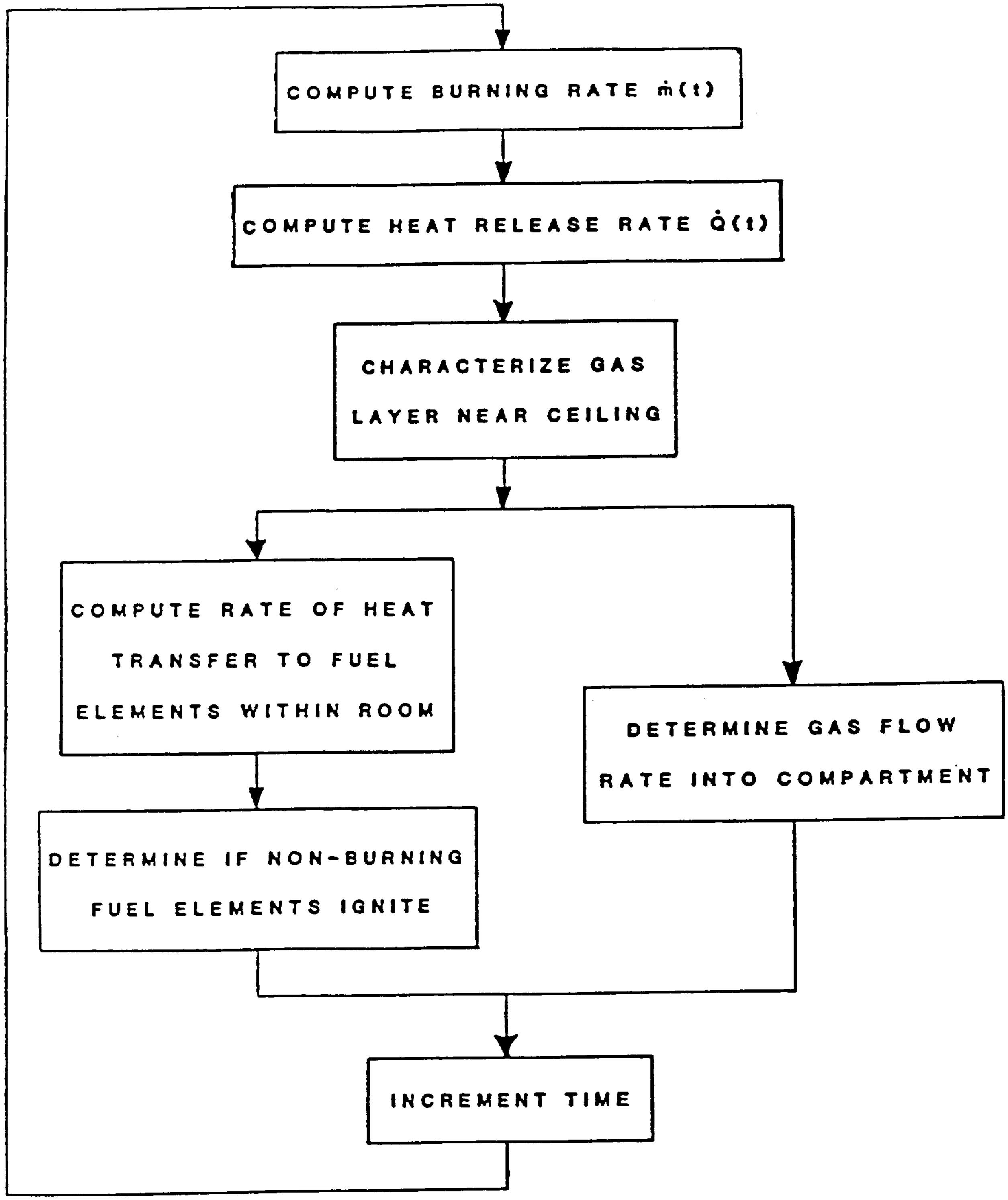
THREE IMPORTANT SCENARIOS





Typical Features in a Zone Model Room Fire Simulation

G. Apostolakis, UCLA



Computational Flow Chart

HEAT RELEASE MODEL

$$\dot{Q} = \eta \dot{m} H_f \qquad \text{(W)}$$

where:

η: burning efficiency

$\dot{m}$: mass burning rate

H_f: total heat of combustion

Ventilation-Controlled Fires

$$\dot{m} = C_V \dot{W}_{IN} \qquad \text{(kg/s)}$$

where:

C_V: proportionality constant dependent upon the type of fuel being burned

$\dot{W}_{IN}$: mass rate of flow of air into the compartment

Fuel-Surface Area Controlled Fires

$$\dot{m}/A_f = \dot{m}'' = \dot{m}''_o + C_s \dot{q}''_{ext} \qquad \text{(kg/m}^2\text{)}$$

where:

$\dot{m}''_o$: fuel-dependent burning rate constant

C_s: burning rate augmentation constant (the inverse of the heat of vaporization)

$\dot{q}''_{ext}$: external heat flux impinging on the fuel element's surface

FUEL ELEMENT THERMAL RESPONSE MODEL

$$\frac{\delta T}{\delta T} = \alpha \frac{\delta^2 T}{\delta x^2}$$

$$-k\left(\frac{\delta T}{\delta x}\right)_{x=0} = h(T_{env} - T_{fe})$$

$$+ \epsilon\sigma(T_{env}^4 - T_{fe}^4) + \dot{q}_{ext}$$

where:

α: thermal diffusivity (m^2/s)

k: thermal conductivity (W/m K)

h: convective heat transfer coefficient (W/m^2 K)

T_{env}: temperature of fuel element's immediate environment (K)

T_{fe}: fuel element surface temperature (K)

ϵ: emissivity of the fuel element

σ: Stefan-Boltzmann constant (5.670×10^{-8} $W/m^2 K^4$)

$\dot{q}''_{ext}$: external heat flux (W/m^2)

MASS TRANSFER MODEL

For the upper region:

$$\dot{W}_E + \dot{W}_{V,IN} = \dot{W}_{OUT} + \dot{W}_{V,OUT}$$

For the lower region:

$$\dot{W}_{IN} + \dot{W}_{U,IN} + \dot{m} = \dot{W}_E + \dot{W}_{U,OUT}$$

For the compartment:

$$\dot{W}_{IN} + \dot{W}_{V,IN} + \dot{W}_{U,IN} + \dot{m} = \dot{W}_{OUT} + \dot{W}_{V,OUT} + \dot{W}_{U,OUT}$$

where:

$\dot{m}$: fuel mass burning rate

$\dot{W}_{U,IN}$: mass flow rate of fresh air into the lower region by forced ventilation

$\dot{W}_{U,OUT}$: mass flow rate of gases out of the lower region by forced ventilation

$\dot{W}_{V,IN}$: mass flow rate of fresh air into the HGL by forced ventilation

$\dot{W}_{V,OUT}$: mass flow rate of hot gases out of the HGL by forced ventilation

$\dot{W}_{IN}$: mass flow rate of incoming fresh air through the doorway

$\dot{W}_{OUT}$: mass flow rate of outgoing hot gases through the doorway

$\dot{W}_E$: mass flow rate of air entrainment due to plume flow ($\dot{W}_{PL}$), wall jet ($\dot{W}_W$), and doorway mixing jet ($\dot{W}_J$)

$$= \dot{W}_{PL} + \dot{W}_W + \dot{W}_J$$

FIRE INDUCED DOOR FLOW
(Rockett's two-zone model)

$$\dot{W}_{OUT} = \frac{2}{3} C_o W_D \rho_0 \left\{ 2g \frac{T_o}{T_G} \left(1 - \frac{T_o}{T_G} \right) \right\}^{1/2}$$

$$\times (H_D - Z_N)^{3/2}$$

$$\dot{W}_{IN} = \frac{2}{3} C_i W_D \rho_0 \left\{ 2g \left(1 - \frac{T_o}{T_G} \right) (Z_N - Z_D) \right\}$$

$$\times \left\{ Z_N + \frac{Z_D}{2} \right\}$$

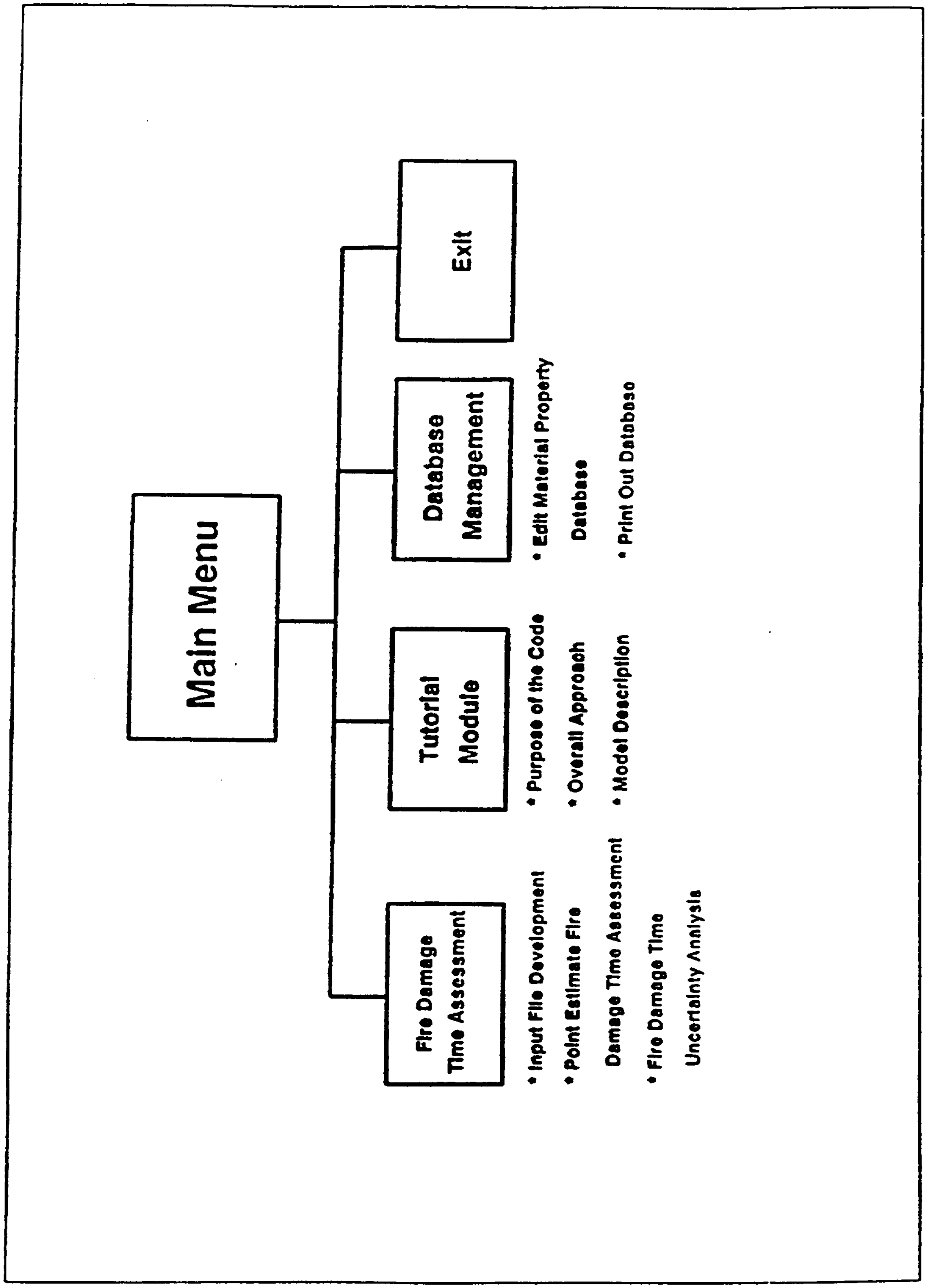
where:

C_i: doorway inflow coefficient

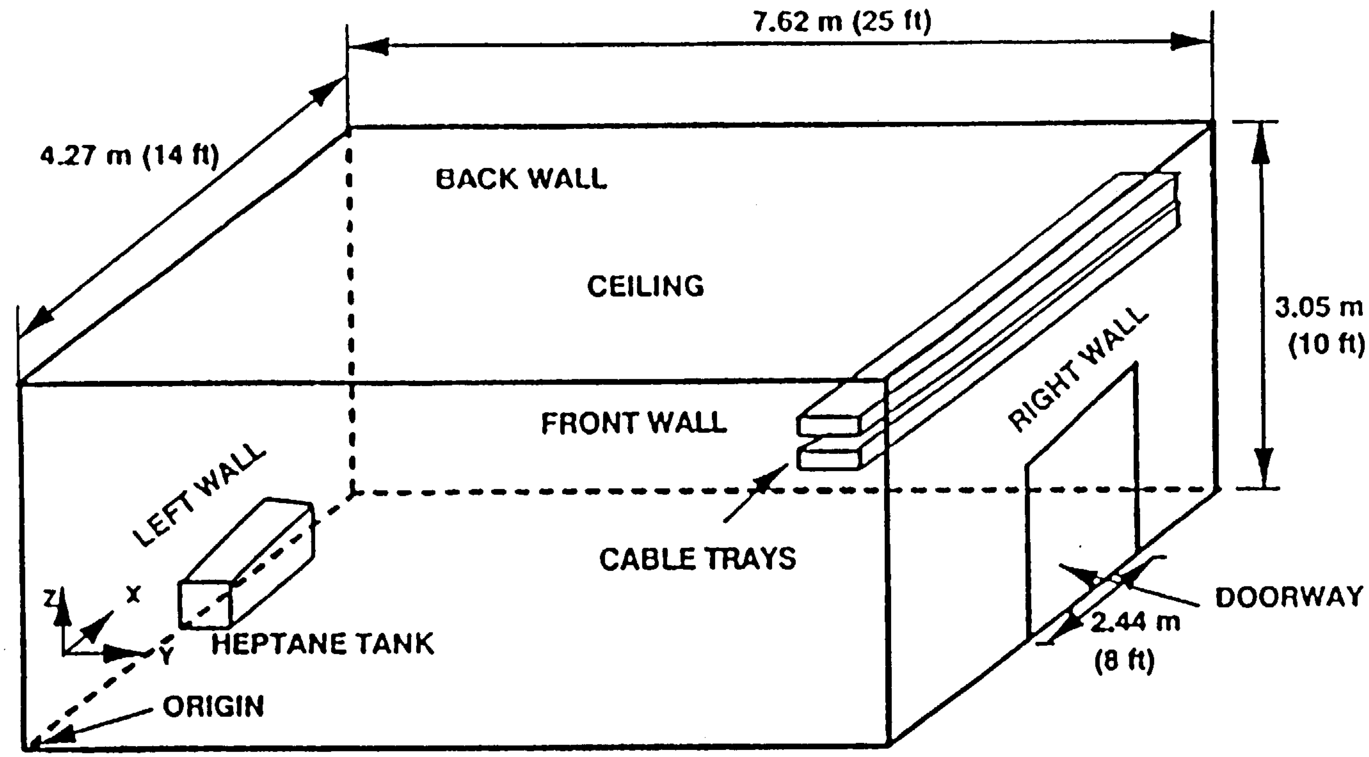
C_o: doorway outflow coefficient

$$C = \dot{W}_{(MEASURED)} / \dot{W}_{(THEORETICAL)}$$

G. Apostolakis, UCLA



The Framework of COMPBRN IIIe



* OBJECTS:
  CEILING
  CABLE TRAYS (TARGET)
  HEPTANE TANK (PILOT)
  WALLS
  (LEFT, RIGHT, FRONT, BACK)

* FUEL TYPE (MATERIAL TYPE):
  CEILING (CONCRETE)
  CABLE (GENERIC)
  SOLVENT (HEPTANE)
  WALL (CONCRETE)

Illustration of the Computer Model for Experiment 2

NASA FIRE SAFETY PROGRAM

OBJECTIVES

- TO INCREASE THE UNDERSTANDING OF FIRE BEHAVIOR IN THE SPACE ENVIRONMENT AND TO APPLY THE RESULTS FOR IMPROVED AND EFFICIENT FIRE PREVENTION, DETECTION, AND SUPPRESSION IN SPACECRAFT

POLICY

- REALISTIC SAFETY PHILOSOPHY IS TO MINIMIZE FIRE RISK AND AVOID CREW INJURY OR ANY SPACECRAFT DAMAGE THAT THREATENS THE MISSION

TECHNOLOGY CHALLENGES

- UNUSUAL FIRE BEHAVIOR IN LOW GRAVITY
- LITTLE PAST EXPERIENCE FOR ACCURATE RISK PREDICTIONS
- EXTREME HIGH VALUE OF SPACECRAFT AND MISSION OPERATIONS
- LIMITED RESOURCES TO PROVIDE FOR COMPLETE FIRE PROTECTION

R. Friedman, NASA Lewis

SPACECRAFT FIRE-SAFETY STATE OF THE ART

PREVENTION	• LARGE DATABASE AVAILABLE ON ACCEPTABLE "NON-FLAMMABLE" MATERIALS, BASED ON NORMAL GRAVITY EVALUATIONS • LIMITED LOW-GRAVITY DATA ON FLAMMABILITY OF THIN SOLID FUELS AND THE INFLUENCE OF LOW-VELOCITY VENTILATION ON FLAMMABILITY
FIRE DETECTION	• AIRPLANE SMOKE DETECTOR DESIGNS ADAPTED TO SPACECRAFT • NO SPACE-RELATED DATA
FIRE EXTINGUISHMENT	• SPACECRAFT EXTINGUISHING AGENTS SELECTED BY SYSTEMS ANALYSES • LIMITED LOW-GRAVITY DATA ON THE INFLUENCE OF ATMOSPHERIC DILUENT GASES ON FLAME SPREAD AND FLAMMABILITY LIMITS

R. Friedman, NASA Lewis

PROBLEMS IN FIRE PREVENTION FOR SPACECRAFT

- MANY COMMON ITEMS, PARTICULARLY COMMERCIAL INSTRUMENTS AND PERSONAL USE ITEMS, CANNOT PASS THE FLAMMABILITY TESTS. THESE EXCEPTIONS ARE PERMITTED ONBOARD SPACECRAFT WHEN CONTROLLED THROUGH ISOLATION, STORAGE PROTECTION, OR BARRIERS. NEVERTHELESS,
  - CONFIGURATION CHANGES MAY OCCUR DURING MISSIONS,
  - FOAM MATERIALS, VELCRO PATCHES, ETC., POSE SPECIAL FLAMMABILITY PROBLEMS (SMOLDERING, PARTICLE EXPULSION).

- FIRE HAZARDS MAY INCREASE IN FUTURE LONG-DURATION OR SPACE STATION MISSIONS, BECAUSE OF THE
  - GREATER VARIETY OF COMMERCIAL AND TEST MATERIALS,
  - HIGHER PROBABILITY OF EXPOSURE TO IGNITION "INCIDENTS",
  - RELAXATION OF ALERTNESS AND SAFETY ATTITUDES WITH TIME.

- CURRENT UNDERSTANDING OF MICROGRAVITY COMBUSTION RAISES QUESTIONS ON THE CORRELATION OF NORMAL-GRAVITY TEST ACCEPTANCE STANDARDS TO THE PREDICTION OF MATERIAL FLAMMABILITY IN LOW GRAVITY.

R. Friedman, NASA Lewis

PROBLEMS IN FIRE DETECTION FOR SPACECRAFT

- THE EFFECTIVENESS OF STANDARD SENSORS IN RESPONDING TO THE UNIQUE CHARACTERISTICS OF MICROGRAVITY FIRES IS UNCERTAIN:
  - FOR SMOKE DETECTION, TYPICAL PARTICLE SIZE, SIZE DISTRIBUTION, AND DENSITY ARE UNKNOWN;
  - FOR SMOKE AND THERMAL DETECTION, HEAT AND MASS TRANSPORT OF FIRE "SIGNATURES" MAY BE SLOW AND UNPREDICTABLE;
  - FOR RADIATION DETECTION, SENSORS MUST RESPOND TO STEADY FLAMES (FLICKER CIRCUITS TO REJECT STRAY LIGHT ARE INEFFECTIVE), AND TYPICAL TEMPERATURES AND EMISSIVITIES ARE UNKNOWN.
- SPECIFIC FIRE SCENARIOS AND RISK MODELS, NECESSARY TO GUIDE OPTIMUM SENSOR SPACING AND LOCATION, ARE LACKING.
- TRADEOFFS FOR OPTIMUM DECISIONS ON SENSITIVITY VS. FALSE ALARMS, MANUAL VS. AUTOMATED RESPONSES, AND SO FORTH, ARE LACKING.

R. Friedman, NASA Lewis

PROBLEMS IN FIRE EXTINGUISHMENT AND CLEANUP IN SPACECRAFT

- THERE IS A LIMITED SELECTION OF USEFUL EXTINGUISHING AGENTS FOR SPACECRAFT USE. MOST SOLID, LIQUID, AND MIXED-PHASE (FOAM) CANDIDATES ARE IMPRACTICAL FOR REASONS OF EXCESSIVE STORAGE MASS, ATMOSPHERIC POLLUTION FROM AGENT LEAKAGE, ELECTRICAL CONDUCTIVITY, POST-FIRE CLEANUP DIFFICULTY, AND SO ON.
- HALON 1301 AND SIMILAR HALOCARBONS ARE TO BE PHASED OUT OF USE IN NEXT DECADE BY INTERNATIONAL AGREEMENTS.
- EFFICIENT LOCALIZED DELIVERY AND DISPERSAL OF ANY AGENT IN THE MICROGRAVITY ENVIRONMENT HAVE YET TO BE DEMONSTRATED.
- FOR THE PERMANENT ORBITAL MISSIONS OF *FREEDOM*, THE LONG-TERM TOXIC AND CORROSIVE EFFECTS OF AGENT AND PRODUCT RESIDUES ARE SERIOUS CONCERNS.

R. Friedman, NASA Lewis

SPACE STATION *FREEDOM* FIRE PROTECTION DESIGN FEATURES

- OCCUPIED VOLUMES ARE ARRANGED AS CONNECTED SERIES OF MODULES AND NODES, ANY OF WHICH CAN BE ISOLATED IN CASE OF A FIRE.
- ADDITIONAL AIR STORES (IN CASE THE ATMOSPHERE IS RELEASED) ARE SUFFICIENT TO REPRESSURIZE ONE MODULE, PLUS ONE NODE, PLUS A HYPERBARIC CHAMBER, EVERY 90 DAYS.
- FIRE DETECTORS SENSE SMOKE (PHOTOELECTRIC) AND RADIATION (UV-IR-VISIBLE).
- FIXED AND PORTABLE FIRE EXTINGUISHERS USE CO_2 AS THE SPECIFIED AGENT IN ALL MODULES, BUT N_2 IS PROPOSED FOR THE PORTABLE EXTINGUISHERS PROTECTING THE HYPERBARIC CHAMBER.
- IN CASE OF A FIRE IN A RACK, AIR FLOW AND POWER TO THE RACK ARE TURNED OFF; SUPPRESSION IS AUTOMATIC.
- IN CASE OF A FIRE IN A MODULE OR NODE, GENERAL VENTILATING AND COOLING AIR ARE TURNED OFF; SUPPRESSION IS AUTOMATIC OR MANUAL.

R. Friedman, NASA Lewis

SPACE STATION *FREEDOM* FIRE-DETECTION PERFORMANCE
(NASA MARSHALL & BOEING REQUIREMENTS)

SMOKE AND OBSCURATION:

SENSITIVITY FOR SMOLDERING:	TO ALARM AT OBSCURATION OF 0.5%/0.3m
SENSITIVITY FOR VISIBLE FIRE:	TO ALARM AT PARTICLE DENSITY OF $1.5 \times 10^9/0.03m^3$
DETECTOR RESPONSE TIME:	30s

FLAME:

SENSITIVITY:	TO ALARM AT $0.09\text{-}m^2$ FLAME AREA VIEWED FROM DISTANCE OF 15m
DETECTOR RESPONSE TIME:	150ms
IMAGE REJECTION:	"BLIND" TO SOLAR RADIATION

THERMAL *(NOT INCLUDED IN CURRENT DESIGNS)*:

SENSITIVITY:	TO RESPOND TO CHANGE OF 8C/min; MAXIMUM TEMPERATURE OF EXPOSED SURFACES LIMITED TO 45C
DETECTOR RESPONSE TIME:	500ms TO REACH 63.2% OF INSTANTANEOUS TEMPERATURE CHANGE
ACCURACY:	1% OVER RANGE OF 17 - 41C

R. Friedman, NASA Lewis

PROBLEMS IN SPACE STATION *FREEDOM* FIRE PROTECTION

- THE COMPLEX CONFIGURATIONS, VARIED CREW ACTIVITIES, AND SCIENTIFIC AND COMMERCIAL OPERATIONS INTRODUCE ADDITIONAL FIRE HAZARDS.
- LONG-DURATION ORBITAL MISSIONS INCREASE THE PROBABILITY OF EXPOSURE TO POTENTIAL FIRE "EVENTS."
- DURING THE INITIAL ASSEMBLY PERIOD, THERE IS THE ADDED HAZARD OF INCREASED MATERIAL FLAMMABILITY IN HIGHER-O_2-CONCENTRATION ATMOSPHERES (REQUIRED FOR EXTRAVEHICULAR ACTIVITIES).
- THE TRADE-OFFS REQUIRED BETWEEN MANUAL AND AUTOMATED FIRE PROTECTION ARE UNRESOLVED; AN AUTOMATED DATA MANAGEMENT SYSTEM MAY FAIL DURING A FIRE, FOR EXAMPLE.
- APPLICATIONS OF THE LIMITED KNOWLEDGE OF LOW-GRAVITY FIRE BEHAVIOR TOWARD PRACTICAL FIRE-PROTECTION HARDWARE AND OPERATIONS FOR SPACE ARE IN A VERY EARLY STAGE OF DEVELOPMENT.
- SEVERE DESIGN CONSTRAINTS ON POWER, MASS, AND VOLUME DEMAND SIMPLE YET HIGHLY EFFICIENT DETECTION-SUPPRESSION SYSTEMS.

R. Friedman, NASA Lewis

RISK-BASED FIRE SAFETY EXPERIMENT (UCLA-NASA)

- ORIGINAL PROPOSAL WAS A RESPONSE TO NASA ANNOUNCEMENT OF OPPORTUNITY, A.O. NO. OAST 1-89
- TECHNICAL REVIEWERS FOUND THAT THE PROPOSED EXPERIMENT WAS VALID AND RELEVANT TO NASA SPACE GOALS, ADDRESSING CRITICAL NEEDS IN SPACECRAFT FIRE SAFETY
- PROPOSED EXPERIMENT, HOWEVER, WAS NOT FEASIBLE FOR A FLIGHT EXPERIMENT; REQUIREMENTS AND FUNDING WERE UNREALISTIC
- PROPOSAL WAS REVISED TO AN EXPANDED PHASE A FEASIBILITY STUDY COMBINED WITH LABORATORY GROUND-BASED EXPERIMENTS
- COMPLETION OF PHASE B UP TO THE FLIGHT EXPERIMENT REVIEW IS INCLUDED AS AN OPTIONAL TASK IN THE REVISED PROPOSAL, TO BE EXERCISED IF NASA SO CHOOSES

R. Friedman, NASA Lewis

RISK-BASED SPACECRAFT FIRE SAFETY EXPERIMENT

OVERALL OBJECTIVE:

SYSTEMATIC INVESTIGATION AND IMPROVEMENT OF FIRE-SAFETY PRACTICES USING QUANTITATIVE RISK-ANALYSIS METHODS

APPROACH:

DESIGN AND IMPLEMENTATION OF LOW-GRAVITY COMBUSTION EXPERIMENTS TO FURNISH INFORMATION FOR DEVELOPMENT OF APPROPRIATE RISK ANALYSES

JUSTIFICATION:

IN-SPACE EXPERIMENTS ESSENTIAL FOR DEMONSTRATION AND INVESTIGATION OF LOW-GRAVITY FIRE CHARACTERISTICS AT REALISTIC SPATIAL AND TIME SCALES

R. Friedman, NASA Lewis

EXPANDED APPROACH FOR RISK-BASED FIRE SAFETY PROJECT

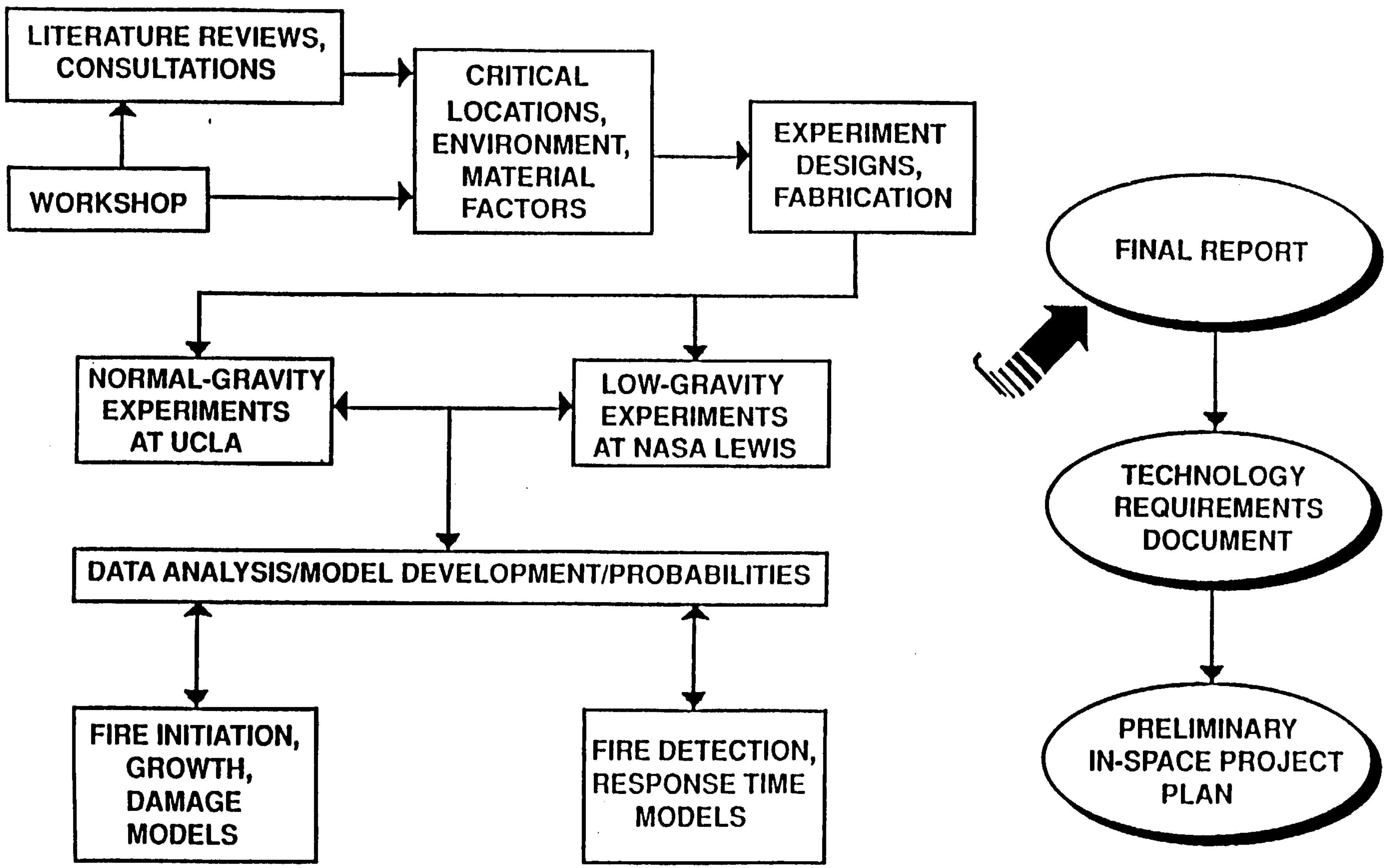
- PRELIMINARY ASSESSMENT TO ESTABLISH FIRE-INITIATION SCENARIOS, EXPERIMENT AND ANALYSIS REQUIREMENTS

- EXPERIMENTS ON LOW-GRAVITY FIRE CHARACTERISTICS FOR STUDY MODELS OF SMOKE RELEASE, HEAT TRANSFER, DETECTION, AND SO ON

- ANALYSIS OF STUDY MODEL RESULTS APPLIED TO SCENARIOS TO DETERMINE COMPETITIVE TIME FACTORS FOR FIRE GROWTH, FIRE DETECTION, AND FIRE SUPPRESSION

- OVERALL DEVELOPMENT OF PRELIMINARY RISK ASSESSMENTS, WITH FREQUENCY-TO-SEVERITY TRADE-OFFS BASED ON MODELS AND PROBABILISTIC FACTORS

UCLA WORK PLAN CONCEPTS



R. Friedman, NASA Lewis

PROBABILISTIC FACTORS APPLIED TO SPACECRAFT FIRE SAFETY

1. PROBABILITY OF OCCURRENCE AND LIKELY LOCATION OF FIRE EVENTS — OVERHEATING, SPILLS, SMOLDERING, IGNITION, AND SO FORTH [INITIATING SCENARIO]

2. PROBABILITY OF CONTINUATION OF FACTOR 1 OCCURRENCES — COMPETITION BETWEEN POTENTIAL FIRE SPREAD TIME AND DETECTION RESPONSE TIME [FIRE GROWTH]

3. PROBABILITY OF EXPANSION OF FACTOR 2 FIRES — DEGREE OF DAMAGE TO PROCESSES OR MISSION [FIRE SEVERITY]

R. Friedman, NASA Lewis

NASA LEWIS PROJECTS IN SPACECRAFT FIRE SAFETY

MATERIAL-FLAMMABILITY TEST ASSESSMENT — NORMAL GRAVITY	NIST
RISK-BASED FIRE-SAFETY EXPERIMENT DEVELOPMENT — NORMAL GRAVITY AND LOW GRAVITY	UCLA
MODELING OF RADIATIVE IGNITION AND SUBSEQUENT FLAME SPREAD — NORMAL GRAVITY	NIST
VENTILATION EFFECTS ON FLAME SPREAD — LOW GRAVITY	IN-HOUSE
SMOKE AND EMISSION INVESTIGATION — LOW GRAVITY	IN-HOUSE
DILUENT AND ATMOSPHERIC EFFECTS — LOW GRAVITY	IN-HOUSE

R. Friedman, NASA Lewis

AN INTEGRATED STRUCTURE FOR TECHNICAL ISSUE RESOLUTION*

a physically based methodology that integrates experiments, analysis and qualifications

OBJECTIVES

- To integrate experiments, analysis and uncertainty qualification by means of a methodology that is systematic, comprehensive, auditable and practical.

- To ensure that special models or computer codes used to resolve a safety issue have the capability to scale-up processes to relevant conditions.

- To provide a proper balance between experiment and analysis and assure a cost-effective resolution of a safety issue.

A method developed by Dr. Novak Zuber to address complex technical issues.

SUCCESS CRITERIA

A complete description of the specific issue being addressed, including identification of the criteria by which successful resolution of the technical issue will be judged.

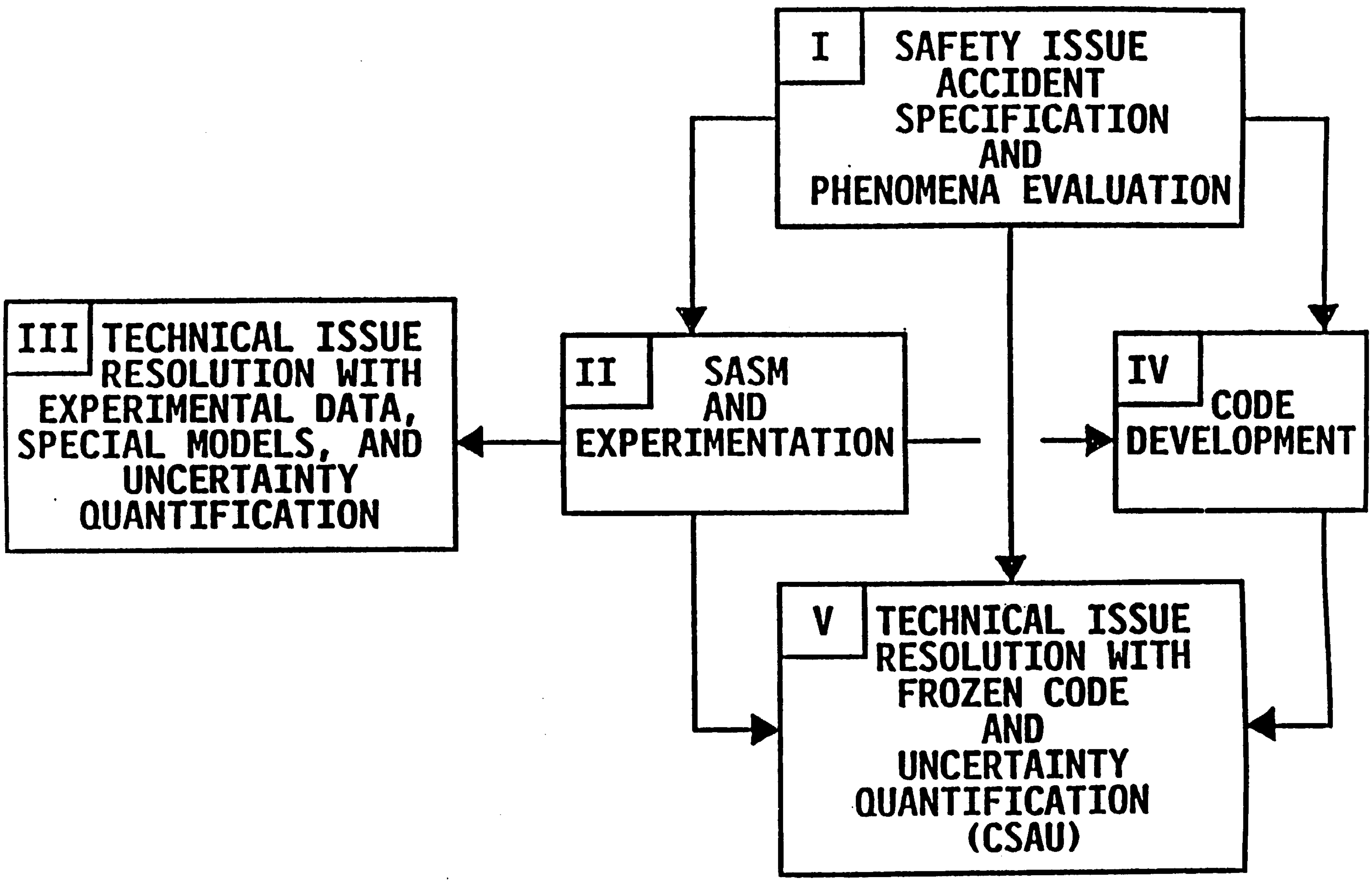
A complete specification of the initiator, the vehicle and the subsequent accident path germane to the issue under investigation.

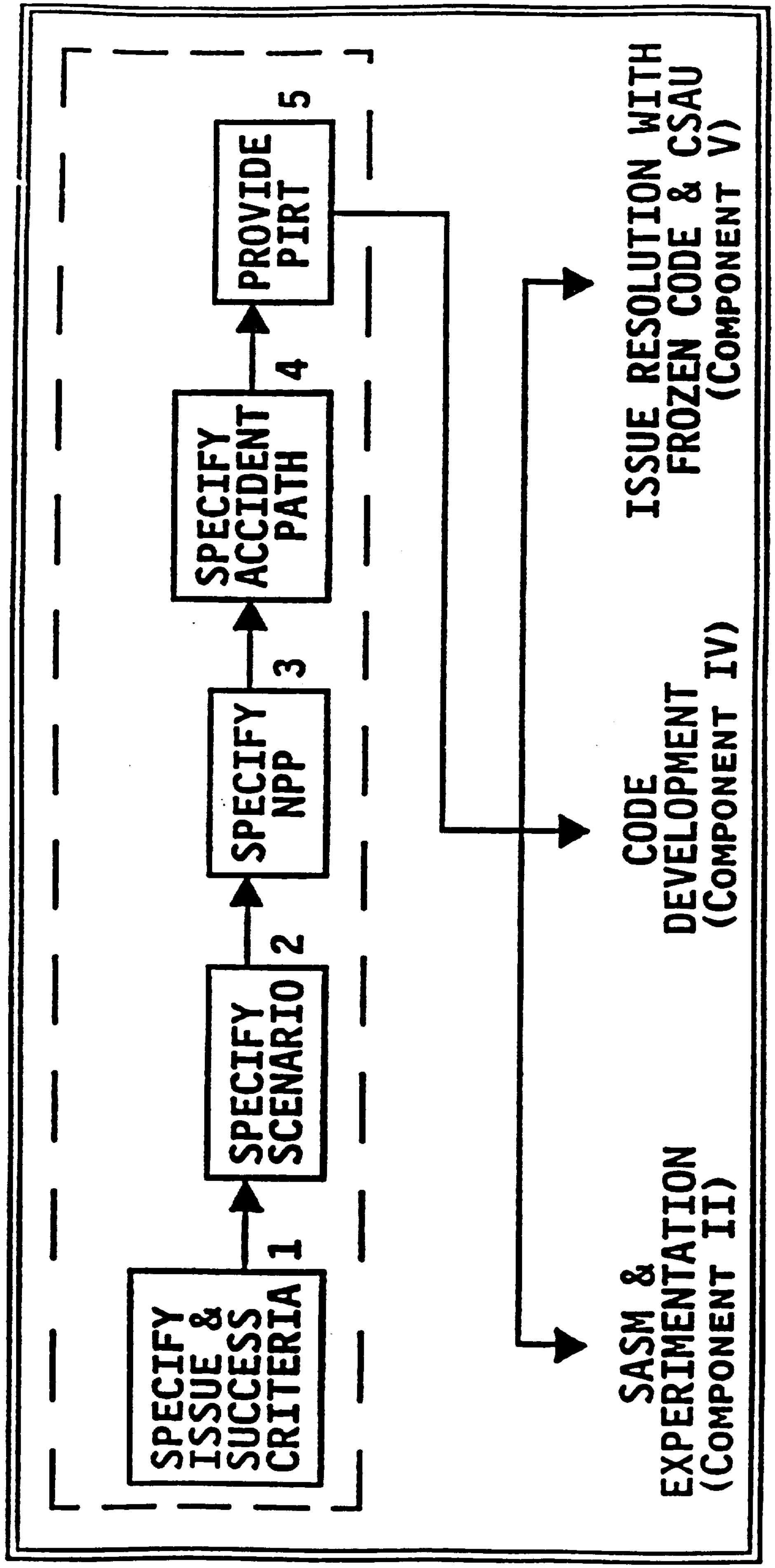
Identification of the plausible phenomena which may be exhibited in the accident in the specified event and vehicle followed by a determination of the phenomena that dominate the event.

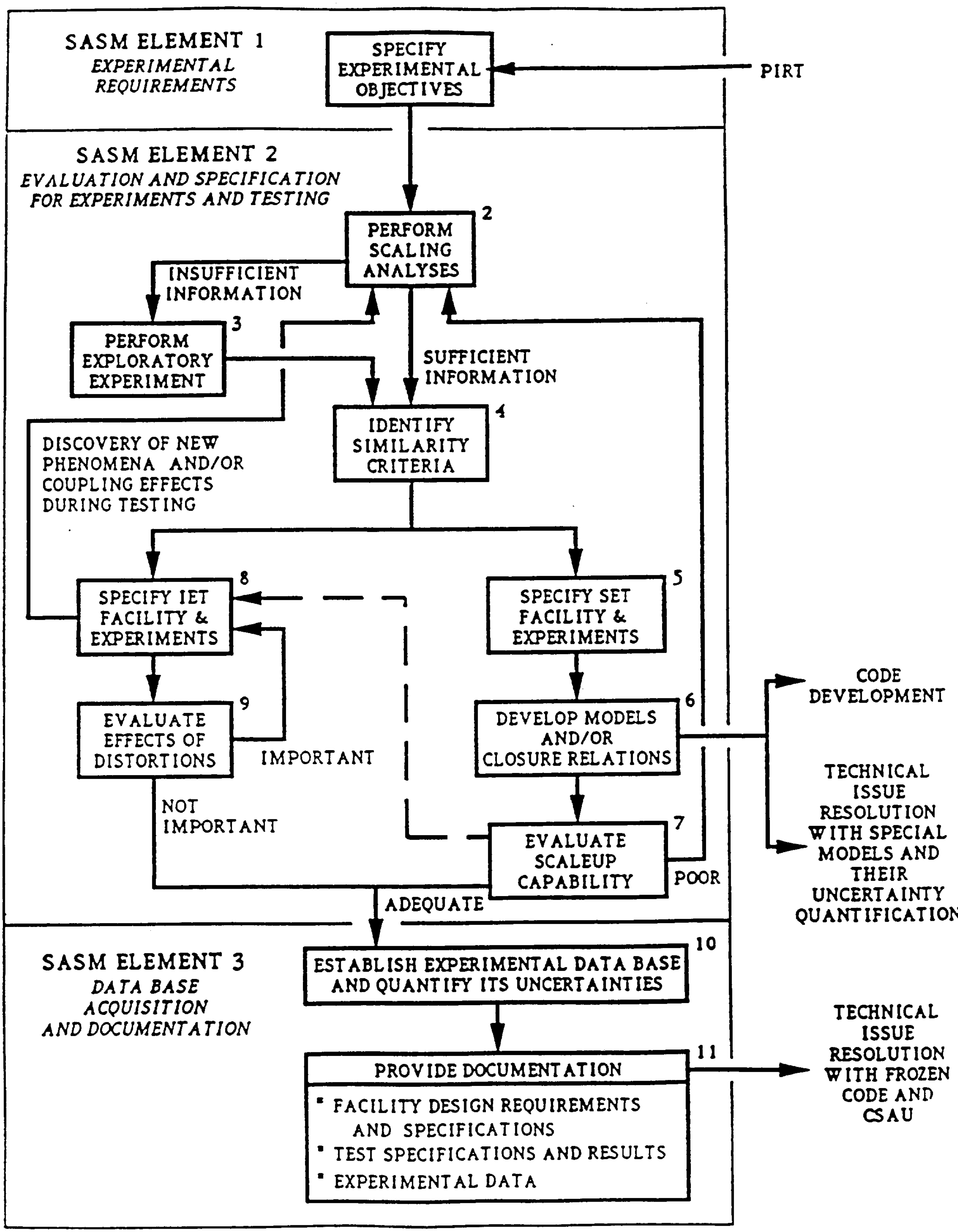
The experimental objectives specified showing a clear basis for and support of resolution of the specific technical issue.

Proper evaluation and specification of the experiments.

I. Catton, UCLA


I SAFETY ISSUE
ACCIDENT
SPECIFICATION
AND
PHENOMENA EVALUATION
II SASM
AND
EXPERIMENTATION
III TECHNICAL ISSUE
RESOLUTION WITH
EXPERIMENTAL DATA,
SPECIAL MODELS, AND
UNCERTAINTY
QUANTIFICATION
IV CODE
DEVELOPMENT
V TECHNICAL ISSUE
RESOLUTION WITH
FROZEN CODE
AND
UNCERTAINTY
QUANTIFICATION
(CSAU)


SPECIFY ISSUE & SUCCESS CRITERIA
1
SPECIFY SCENARIO
2
SPECIFY NPP
3
SPECIFY ACCIDENT PATH
4
PROVIDE PIRT
5
SASM & EXPERIMENTATION (COMPONENT II)
CODE DEVELOPMENT (COMPONENT IV)
ISSUE RESOLUTION WITH FROZEN CODE & CSAU (COMPONENT V)


SASM ELEMENT 1
EXPERIMENTAL REQUIREMENTS
SPECIFY EXPERIMENTAL OBJECTIVES
PIRT
SASM ELEMENT 2
EVALUATION AND SPECIFICATION FOR EXPERIMENTS AND TESTING
2
PERFORM SCALING ANALYSES
INSUFFICIENT INFORMATION
3
PERFORM EXPLORATORY EXPERIMENT
SUFFICIENT INFORMATION
4
IDENTIFY SIMILARITY CRITERIA
DISCOVERY OF NEW PHENOMENA AND/OR COUPLING EFFECTS DURING TESTING
8
SPECIFY IET FACILITY & EXPERIMENTS
5
SPECIFY SET FACILITY & EXPERIMENTS
9
EVALUATE EFFECTS OF DISTORTIONS
IMPORTANT
NOT IMPORTANT
6
DEVELOP MODELS AND/OR CLOSURE RELATIONS
CODE DEVELOPMENT
TECHNICAL ISSUE RESOLUTION WITH SPECIAL MODELS AND THEIR UNCERTAINTY QUANTIFICATION
7
EVALUATE SCALEUP CAPABILITY
POOR
ADEQUATE
SASM ELEMENT 3
DATA BASE ACQUISITION AND DOCUMENTATION
10
ESTABLISH EXPERIMENTAL DATA BASE AND QUANTIFY ITS UNCERTAINTIES
11
PROVIDE DOCUMENTATION
• FACILITY DESIGN REQUIREMENTS AND SPECIFICATIONS
• TEST SPECIFICATIONS AND RESULTS
• EXPERIMENTAL DATA
TECHNICAL ISSUE RESOLUTION WITH FROZEN CODE AND CSAU

OBJECTIVES OF SEVERE ACCIDENT SCALING METHODOLOGY

1. To provide a scaling methodology that is sytematic and practical, auditable and traceable,

2. To provide the scaling rationale and similarity criteria,

3. To provide a procedure for conducting comprehensive reviews of facility design, of test conditions and results,

4. To ensure the prototypicality of the experimental data, and

5. To quantify biases due to scale distortions or due to non-prototypical conditions.

THE TWO TIERED APPROACH

The top-down approach scales the behavior of the whole system (synergism) whereas the bottom-up approach focuses on specific processes (monergism).

Specific mechanisms found to be important to the whole are investigated at the lower level, their significance is synthesized and evaluated at the top one.

Together the two approaches provide a methodology that is practical and that yields technically justifiable results.

Scaling is determined by the question addressed, that is, by the details of information one seeks.

As information details are reflected in hierarchical levels, scaling is determined by the level of resolution, that is, by the hierarchical level at which the problem is to be formulated.

The number of scaling groups decreases with increasing hierarchical level.

The scaling groups are constraints on the experimenter, the lower hierarchical level having more constraints.

Reduction in constraints at higher hierarchical level is paid for by a loss of information content and details.

As more detailed and specific questions arise that need to be addressed at lower hierarchical levels, the more constraints must be met.

SPACE STATION FREEDOM QUANTITATIVE RISK ASSESSMENT PROGRAM

by
William R. Fuller
B. John Garrick
James C. Lin

Presented to
WORKSHOP ON SPACECRAFT FIRE SAFETY
University of California, Los Angeles
October 31, 1991

PLG
Newport Beach ■ CA
Washington ■ DC

ENGINEERS ■ APPLIED SCIENTISTS ■ MANAGEMENT CONSULTANTS

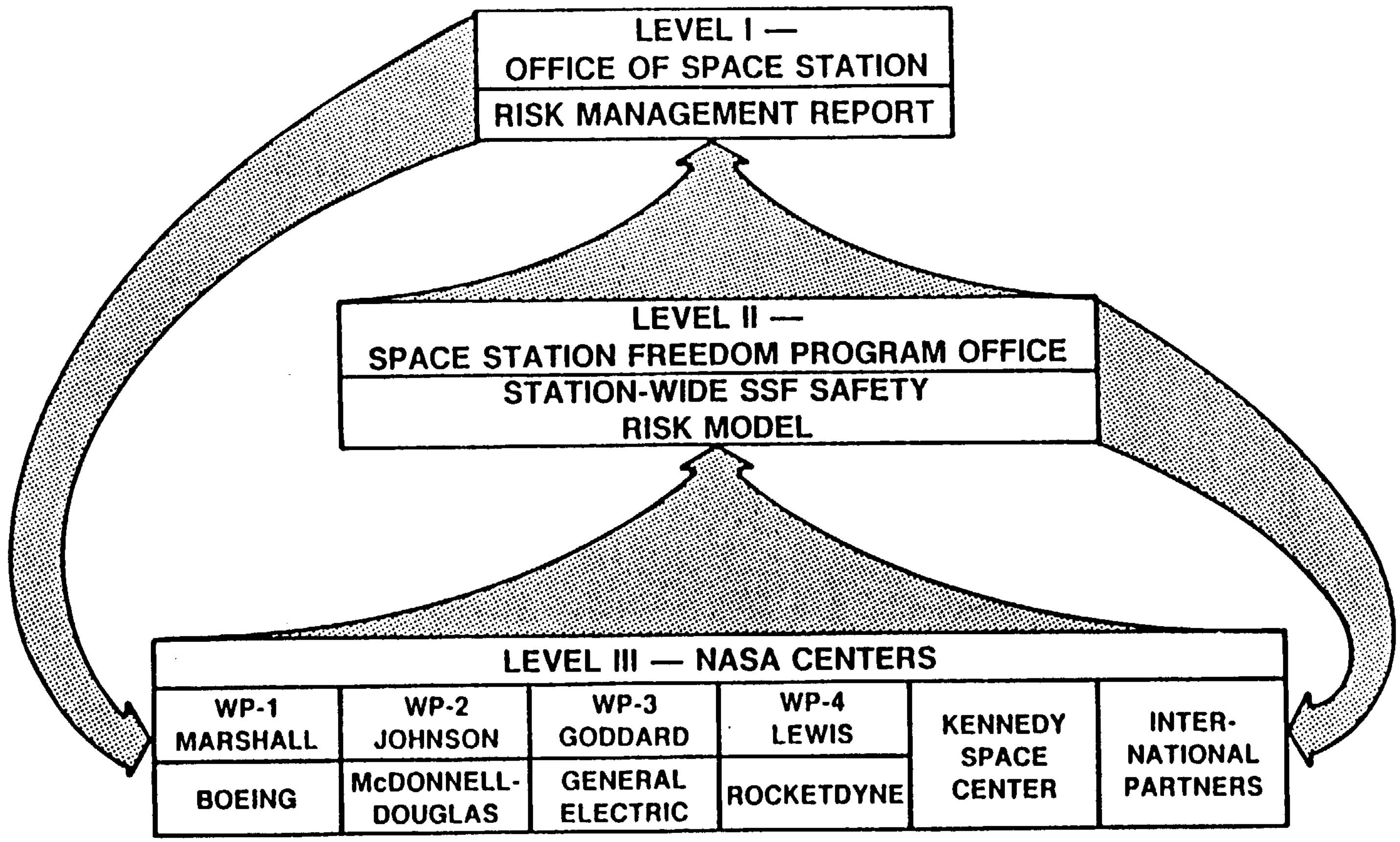
W. Fuller, PLG, Inc.

OBJECTIVES

- DEVELOP AN INTEGRATED, TOP-LEVEL SPACE STATION RISK ASSESSMENT MODEL
- USE DETAILED SAFETY AND RELIABILITY ANALYSES FROM LEVELS II, III, AND IV TO ENHANCE AND QUANTIFY TOP-LEVEL RISK MODEL
- INTEGRATE SAFETY RISK ASSESSMENT PROCESS INTO THE DESIGN, TEST, ANALYSIS, AND OPERATIONS PROCESSES AT ALL LEVELS
- PROVIDE INPUTS TO MANAGEMENT TO SUPPORT DECISION MAKING; i.e., RISK MANAGEMENT

PLG

SSF SAFETY RISK ASSESSMENT PROCESS



- HAZARD ANALYSES
- FMEA/CILS
- RELIABILITY PREDICTIONS
- STRESS ANALYSES
- THERMAL ANALYSES
- ENVIRONMENTAL ANALYSES
- •
- •
- •

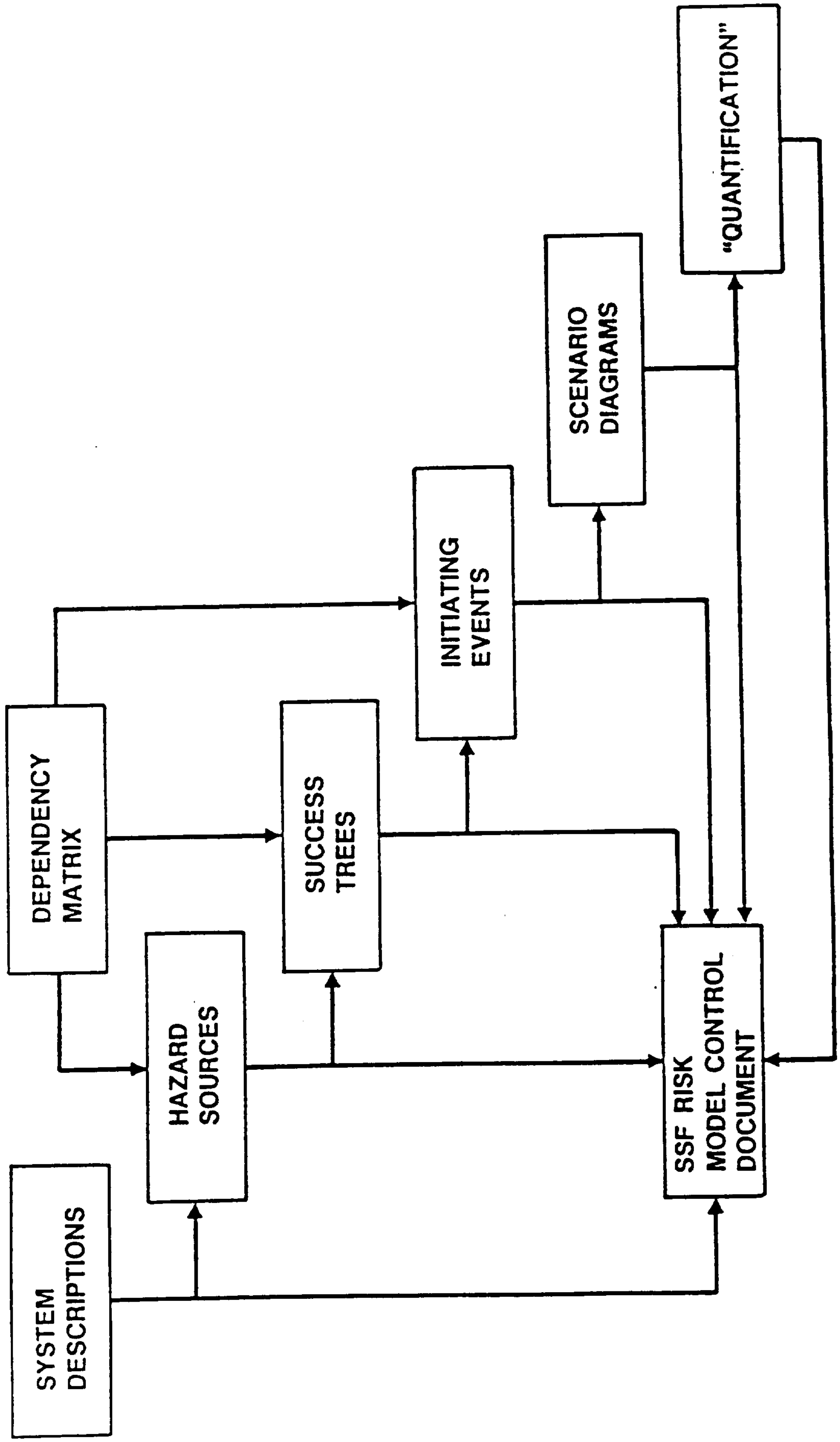
- COMMON CAUSE FAILURE ANALYSES
- HUMAN FACTORS ANALYSES
- SNEAK CIRCUIT ANALYSES
- AGING AND USEFUL LIFE ANALYSES
- •
- •
- •

RISK MANAGEMENT GOALS

- NASA MANAGEMENT INSTRUCTION, NMI 8070.4, RISK MANAGEMENT POLICY FOR MANNED FLIGHT PROGRAMS, FEBRUARY 3, 1988.
  - POLICY REINFORCED NASA'S COMMITMENT TO QUALITATIVE FMEA/CIL AND HAZARD ANALYSIS TECHNIQUES.
  - POLICY ALSO OPENED THE DOOR FOR FUTURE QRAs.
- SPACE STATION FREEDOM SAFETY PROGRAM PLAN (SSFP 30309) INCLUDES PARALLEL PATHS.
  - TRADITIONAL QUALITATIVE APPROACH (e.g., HAZARD ANALYSIS)
  - SAFETY RISK ASSESSMENT/MANAGEMENT APPROACH.

PLG

SAFETY RISK ASSESSMENT APPROACH



DEPENDENCY MATRIX

THIS ITEM \ PROVIDES SUPPORT TO THIS ITEM		EPS	DMS	GN&C	C&T	TCS	FMS: INS	FMS: IWS	FMS: IWGS
EPS		(1)	(1),(2)	(1),(3)	(1)	POWER TO I&C PUMPS AND VALVES; FAILURE POSITION OF VALVES IS TBD	POWER FOR HEATERS ON TRUSS, COMPRESSORS, VALVES, AND I&C(39)	POWER FOR HEATERS ON TRUSS, VALVES, AND I&C(24)	POWER FOR HEATERS ON TRUSS, VALVES, I&C, AND COMPRESSO TO COMPR GAS FOR STORAGE
DMS		SERVES AS DATA INTERFACE BETWEEN EPS AND REST OF SSMB; PROVIDES CONFLICT RESOLUTION OF POWER DEMANDS(4)	INTERNAL SYSTEM MANAGEMENT(5)	PROVIDES ALL DATA AND SOFTWARE PROGRAMS NEEDED FOR OPERATION OF GN&C	PROVIDES SOFTWARE PROGRAMS NEEDED FOR OPERATION AND COMMUNICATION ON DATABASES	STORES TCS SYSTEM STATUS; PROVIDES FAULT DIAGNOSIS, RE-CONFIGURATION, LOAD CONFLICT RESOLUTION	(34),(40)	(34),(40)	
GN&C		POSITIONS PV PANELS BY DIRECTING VIA THE DMS, THE α GIMBAL ALSO SUPPLIES DATA IN SUPPORT OF β GIMBAL (6)	PROVIDES STORAGE OF GNC DATA FOR COMMUNICATION	(21)	PROVIDES POINTING INFORMATION FOR ANTENNAE FOR INTERFACE WITH TDRSS (12)	COMMANDS GIMBALING OF CATCS RADIATORS VIA DMS(11)	NS (13)	NS (	
C&T		PROVIDES VIDEO SURVEILLANCE OF EQUIPMENT; PROVIDES UPLINK COMMANDS AND DOWNLINK TELEMETRY VIA DMS	VOICE, VIDEO, AND DATA COMMUNICATION (14)	PROVIDES STATE INFORMATION FROM GPS AND TDRSS, VIA DMS, SO SSMB POSITION IS KNOWN(15)	—	(16)	(16)		
TCS		PROVIDES COOLING OF ENERGIZED EQUIPMENT; PROVIDES HEATING OF DEENERGIZED EQUIPMENT ON TRUSS(7)	COOLS POWER-USING EQUIPMENT(7),(8)	(7),(43),(45)	PASSIVE COOLING CURRENTLY ANTICIPATED (45)	(2			
FMS	INS	NS	NS	(40)	NS				
FMS	IWS	NS	NS	(40)					
FMS	IWGS	NS	NS						
ECLSS	THC AND ACS	(41)							
ECLSS	WHM AND AR								

PLG

SOURCES OF HAZARDS — EXTERNAL

Generic	Subclass	Consequence	
		Crew	Station
Collision	With Space Debris	X	X
	With Meteoroids	X	X
	With Payloads	X	X
	With Other Vehicles	X	X
	With MSS or FTS	X	X
Unplanned Re-Entry	Failed Thrust		X
	Uncommanded Thrust	X	X
	Incidental Thrust	X	X
	Late Resupply Mission	X	X
	Extreme Solar Activity or Other Radiation	X	X
	Failed Flight Control	X	X
	Improper Crew or Ground Control Actions	X	X
Radiation	Extreme Solar Activity	X	
	Altitude Too High	X	
	Exposure Too Long	X	
	Breakup of Nuclear-Powered Satellite in the Vicinity	X	
	RF and Microwave Radiation	X	
Insufficient Consumables	Late Resupply Mission	X	
	Loss of Supply due to Leaks	X	
	Loss of Supply due to Spoilage	X	
	Loss of Supply due to Improper Crew Actions	X	

Reference: Pickard, Lowe and Garrick, Inc., "Space Station Freedom Program Risk Model Control Document," (Rev. A), prepared for Grumman Space Station, Program Support Division, PLG-0702, June 1989.

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SOURCES OF HAZARDS — INTERNAL

Generic	Subclass	Consequence	
		Crew	Station
Station Tumbling	Flight Control Fault	X	X
	Thrust Fault	X	X
	Improper Crew or Ground Control Actions	X	X
	Incidental Thrust	X	X
	Mass Movement or Distribution Fault	X	X
Improper Atmospheric Pressure	Loss of Hull Integrity	X	
	Leaky Hull Vent Valve	X	
	Loss of Gas Supply	X	
	Failure of Regulation	X	
	Leaky High-Pressure Tank	X	
	Improper Crew or Ground Control Actions	X	
	Faulty Airlock	X	
	Faulty Extravehicular Activity Suite	X	
Improper Atmospheric Temperature	Loss of Sufficient Power	X	X
	Loss of Passive Protection	X	
	TCS Fault	X	X
	Regulation Fault	X	
	Extravehicular Mobility Unit Fault	X	
	Extreme Thermal Load in Cabin	X	
Atmospheric Contamination	Fault in Waste Systems	X	
	Fault in Air Purification Systems	X	
	Unexpected Contaminant That Cannot Be Filtered	X	
	Fault in Experiments	X	
	Leak in Any Pressurized Fluid Container Fire	X	X
	Use of Fire Extinguisher	X	
Contamination of Water Supply	Fault in Water Purification Systems	X	
	Unexpected Contaminant That Cannot Be Filtered	X	
	Fault in Plumbing	X	

Reference: Pickard, Lowe and Garrick, Inc., "Space Station Freedom Program Risk Model Control Document," (Rev. A), prepared for Grumman Space Station, Program Support Division, PLG-0702, June 1989.

INTERNAL HAZARDS TO THE SSMB

Generic	Subclass	Consequence: Crew	Consequence: Station
Contamination of Food Supply	Spoilage	X	
	Improper Crew Action	X	
Fire, Rapid Oxidation	Electrical Short/Overload	X	X
	Faults in Electrolysis Units	X	X
	Oxygen Leak	X	X
	Chemical Reaction	X	X
	Faulty Experiment	X	X
	Improper Crew or Ground Control Actions	X	X
Accelerated Mass	Explosion	X	X
	Bursting Pipe or Tank	X	X
	FTS Mishap, Runaway Robot	X	X
	Mobile Transporter Mishaps	X	X
	EVA/EMU Mishap	X	
	Faulty Experiment	X	
	Improper Crew Activities	X	
	Hard Docking	X	X
Vibration	Unexpected Structural Resonance		X
	Instability in GN&C Loops	X	X
	Propulsion Out of Control	X	X
	Pump Cavitation		X
	Water Hammer/Fluid Hammer		X
	CMG Out of Balance or Bearing Failure		X
Electric	High-Voltage Shock	X	
	High-Current Burn	X	

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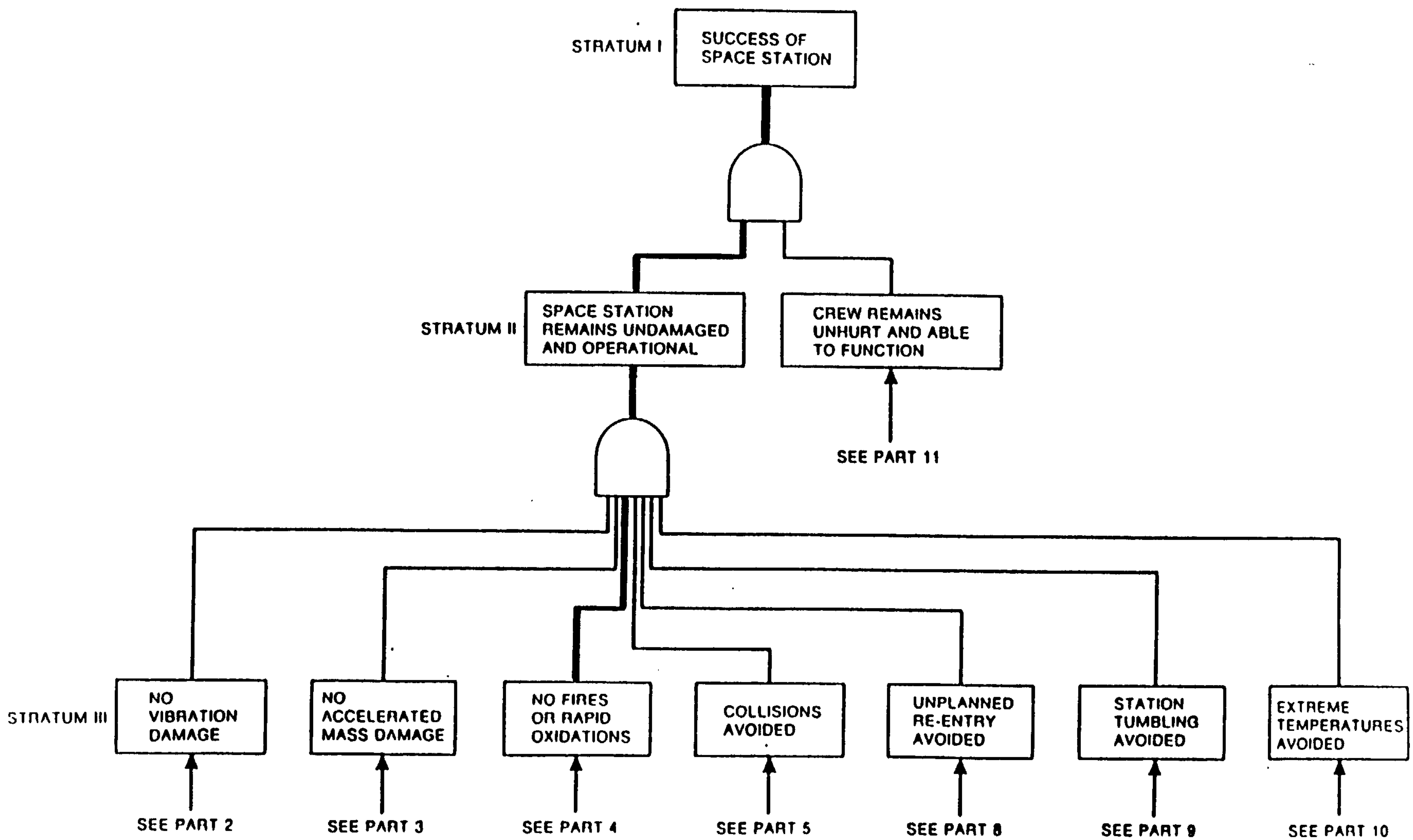
MASTER LOGIC DIAGRAM



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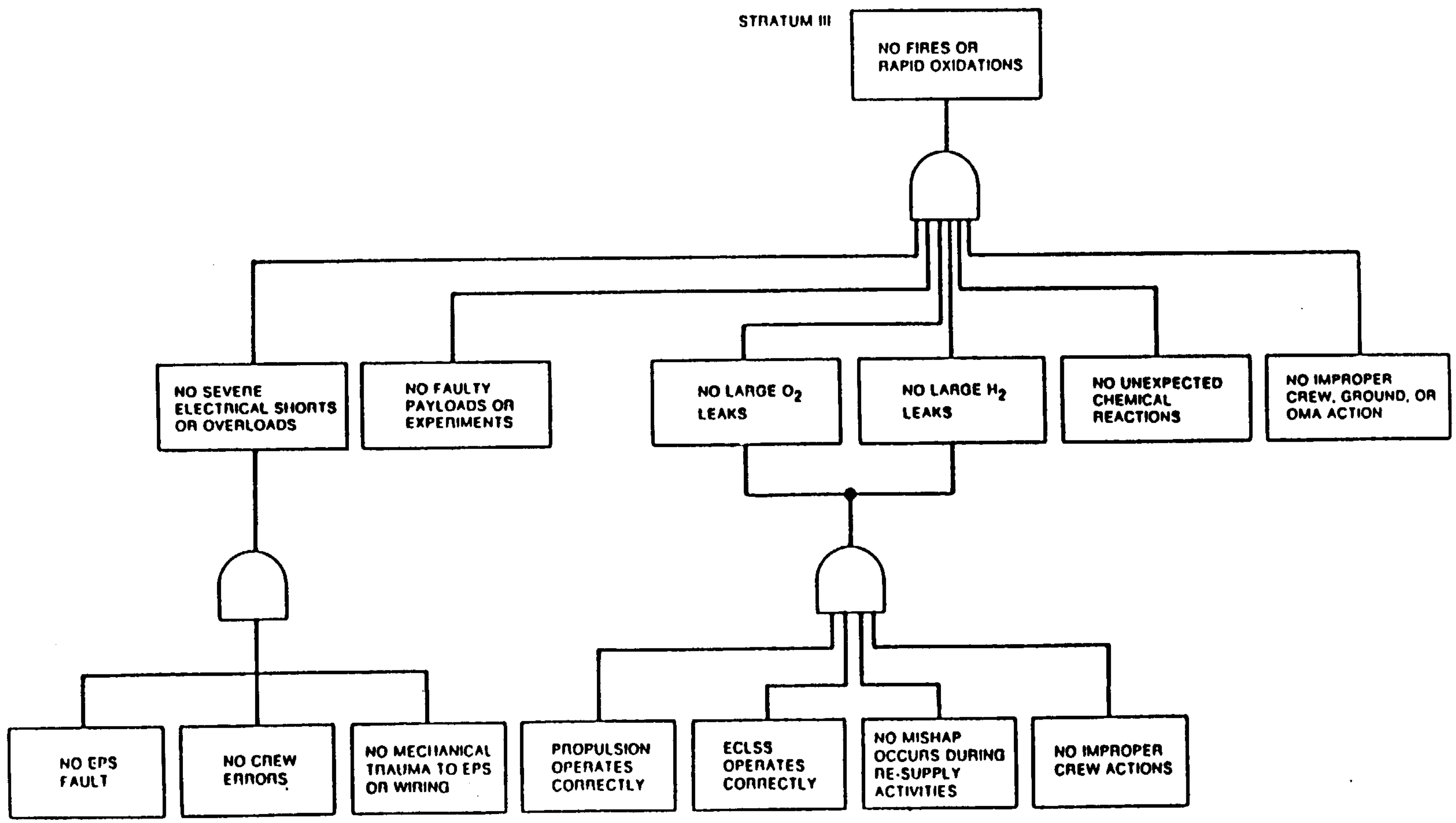
MASTER LOGIC DIAGRAM — PART 4



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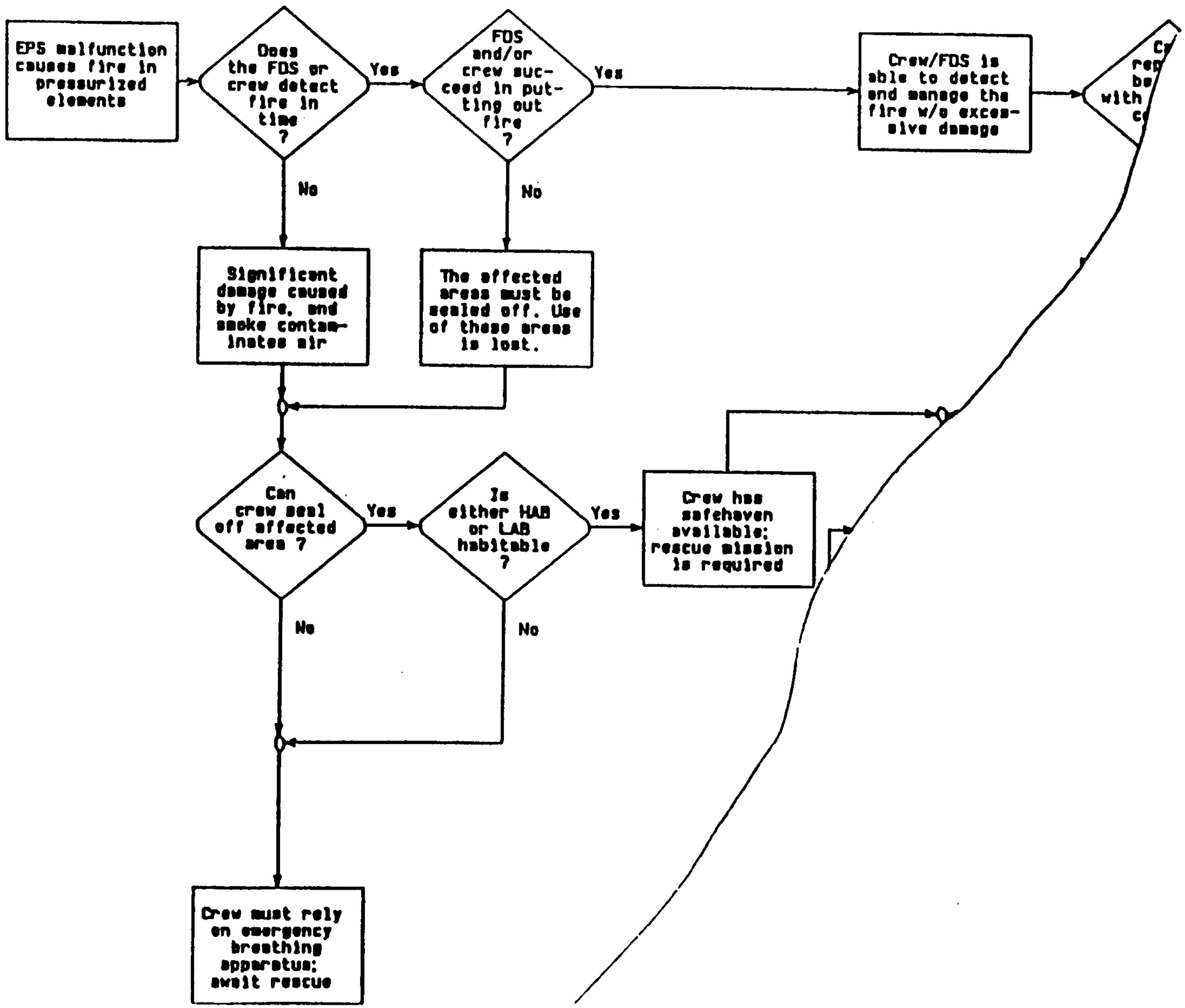
INITIATING EVENTS

Number	Generic Class	Sub Class	Next Level	Next Level
9.01.01	Fire or Rapid Oxidation	Severe Electrical Shorts or Overload	EPS Malfunction	
9.01.02			Mechanical Trauma to Wiring or Equipment	
9.01.03			Crew Errors	
9.02	Fire or Rapid Oxidation	Faulty Payload or Experiment		
9.03.01		Excessive O_2 in Atmosphere or Release Outside Station	Propulsion System Fault	
9.03.02			ECLSS Fault	
9.03.03			Improper Crew, Ground Control, or OMA Actions	
9.03.04			Mishap Occurs during Resupply Activities	
9.03.05			Fault in EVAS Operation	
9.04.01		Excessive H_2 in Atmosphere	Propulsion System Fault	
9.04.02			ECLSS Fault	
9.04.03			Improper Crew, Ground Control, or OMA Actions	
9.04.04			Mishap Occurs during Resupply Activities	

INITIATING EVENTS (Continued)

Number	Generic Class	Sub Class	Next Level	Next Level
9.05		Unexpected Chemical Reactions		
10.01.01	Electrical Hazard	High Voltage	Equipment Short Circuit and a Failed Ground Fault Protection	
10.01.02			Exposed Voltage due to Service or Damage	
10.01.03			Crew Errors	
10.02.01	Electrical Hazard	High Current Burns	Equipment Short or Overload and Faulty Circuit Breaker	
10.02.02			Exposed Voltage due to Service or Damage and Accidental Short	
10.02.03			Crew Errors	
11.01.01.01	Vibration	Structural Resonances Are Excited	GN&C Instabilities	Design Error or Unanticipated Circumstances
11.01.01.02				GN&C Fault
11.01.02			Propulsion Fault	
11.01.03			Pump Cavitation of Fluid Hammering	
11.01.04			Gross Imbalance or Bearing Fault in CMG	

SCENARIO 9.01.01 — EPS MALFUNCTION CAUSES FIRE IN PRESSURIZED ELEMENT



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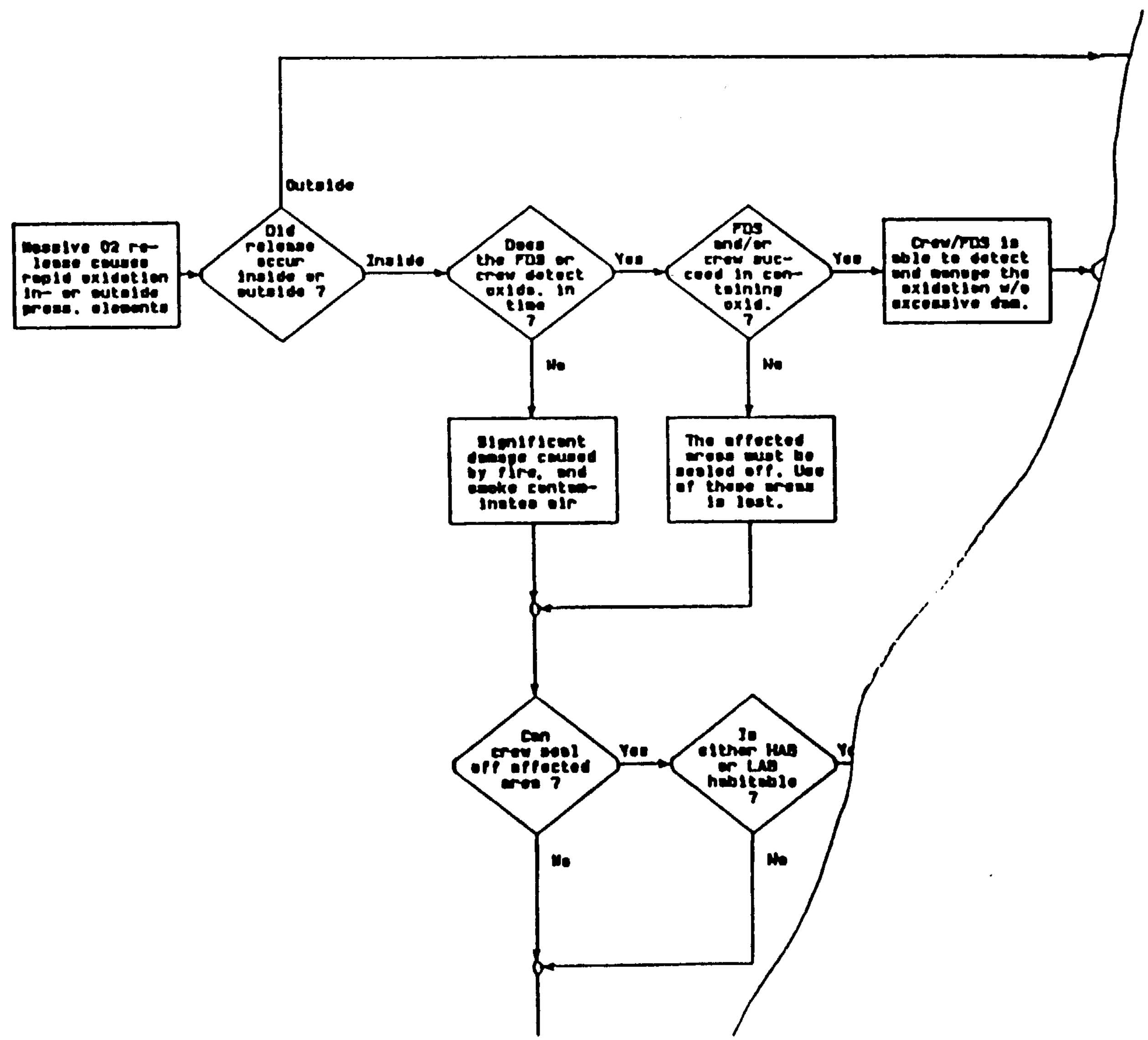
SCENARIO 9.03 — MASSIVE RELEASE OF OXYGEN OR OTHER AGGRESSIVE OXIDANT CAUSES RAPID OXIDATION INSIDE OR OUTSIDE PRESSURIZED ELEMENT



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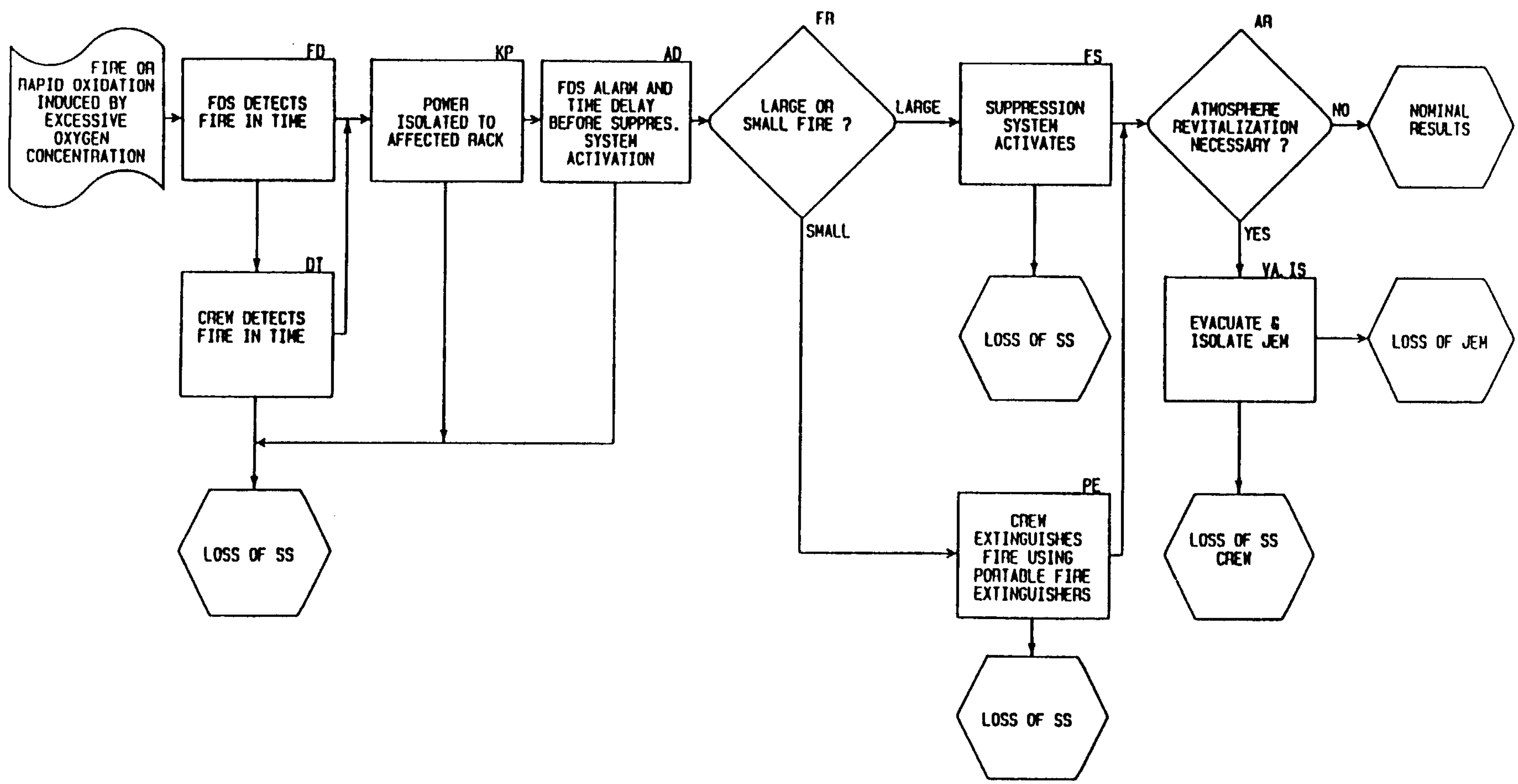
EVENT SEQUENCE DIAGRAM FOR FIRE OR RAPID OXIDATION INDUCED BY EXCESSIVE OXYGEN CONCENTRATION



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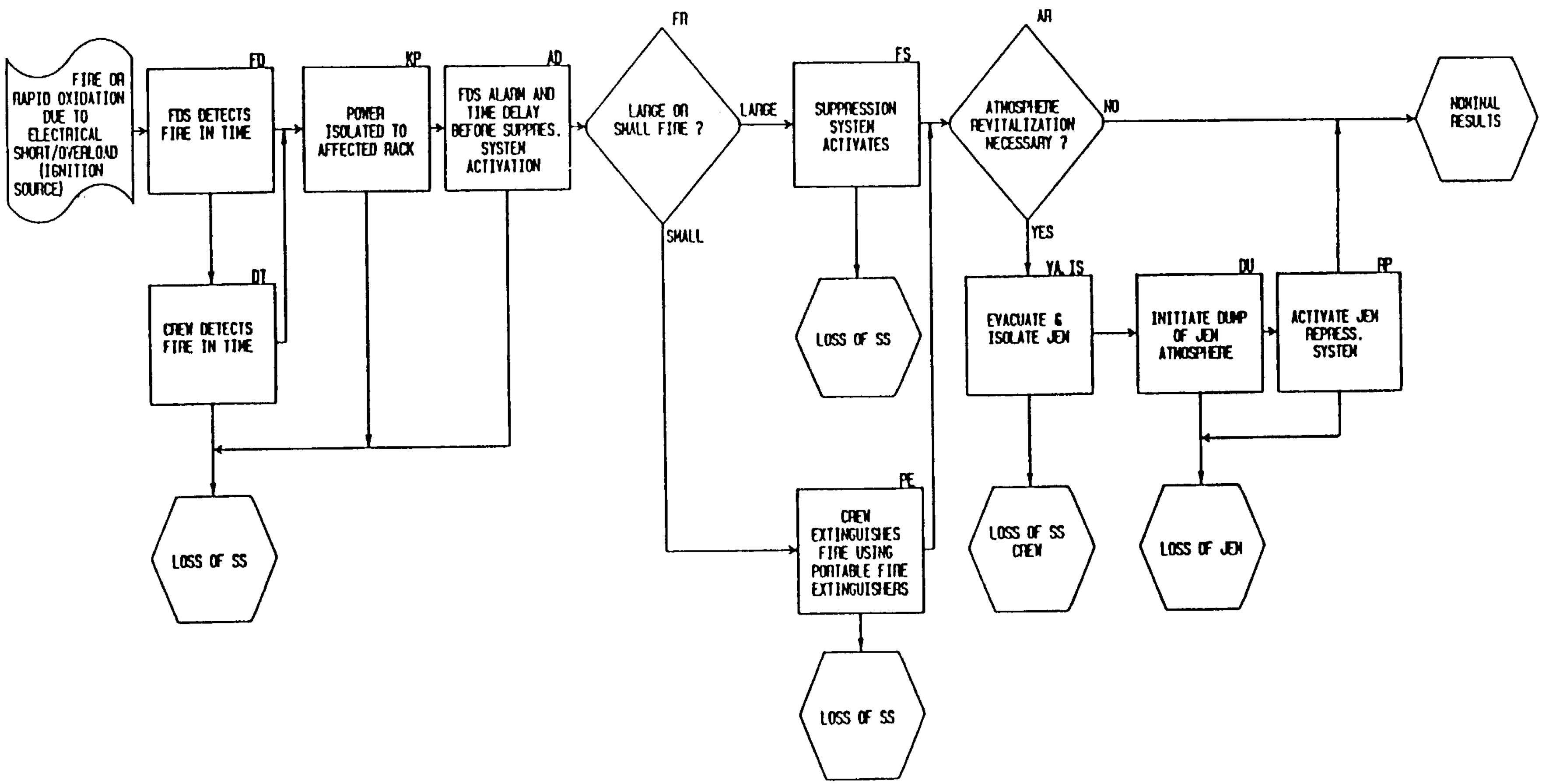
EVENT SEQUENCE DIAGRAM FOR FIRE OR RAPID OXIDATION DUE TO ELECTRICAL SHORT/OVERLOAD (IGNITION SOURCES)



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Effects of Ambient Atmosphere on Flame Spread and Extinguishment

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Supported by the U. S. National Science Foundation
Presidential Young Investigator Program
Grant No. CBT-8657228

Motivation

- Flame spread over thin solid fuels (e.g. paper) - simple model system for two-phase spreading flames

- Effect of ambient atmosphere is frequently an important consideration, e.g. in

  - Vitiated air
  - Atmospheres with unburned fuel or intermediates (e.g. CO) - (*partially premixed* flame spread)
  - Submarines
  - Spacecraft

- Little systematic investigation of atmosphere effects has been conducted

Flame spread theory

- de Ris (1968), Delichatsios (1986)
    - Infinite reaction rate ("mixed is burned")
    - No fuel in ambient atmosphere
- Most important & readily observable characteristic - *flame spread rate* (S_f)

$$S_f = \frac{\pi}{4} \frac{\lambda_g}{\rho_s \tau_s C_{p,s}} \frac{T_f - T_v}{T_v - T_o} \quad \text{(de Ris, Delichatsios)}$$

λ = conductivity, ρ = density, τ = thickness, C_p = heat capacity, T = temperature
g = gas, s = solid, f = flame front, v = vaporization condition, o = ambient condition

$$T_f = T_o + \frac{T_o - T_v + \frac{Y_{ox,o} M_{fu} \nu_{fu}}{M_{ox} \nu_{ox}} \frac{\mathcal{Q} - L}{C_{p,g}}}{1 + \left[\frac{Y_{ox,o} M_{fu} \nu_{fu}}{M_{ox} \nu_{ox}}\right]} \quad \text{(same as 1-D flame!)}$$

Y = mass fraction, M = molecular weight, ν = stoichiometric coefficient,
$\mathcal{Q}$ = heating value of fuel, L = latent heat of vaporization of the fuel bed material
fu = fuel, ox = oxidant

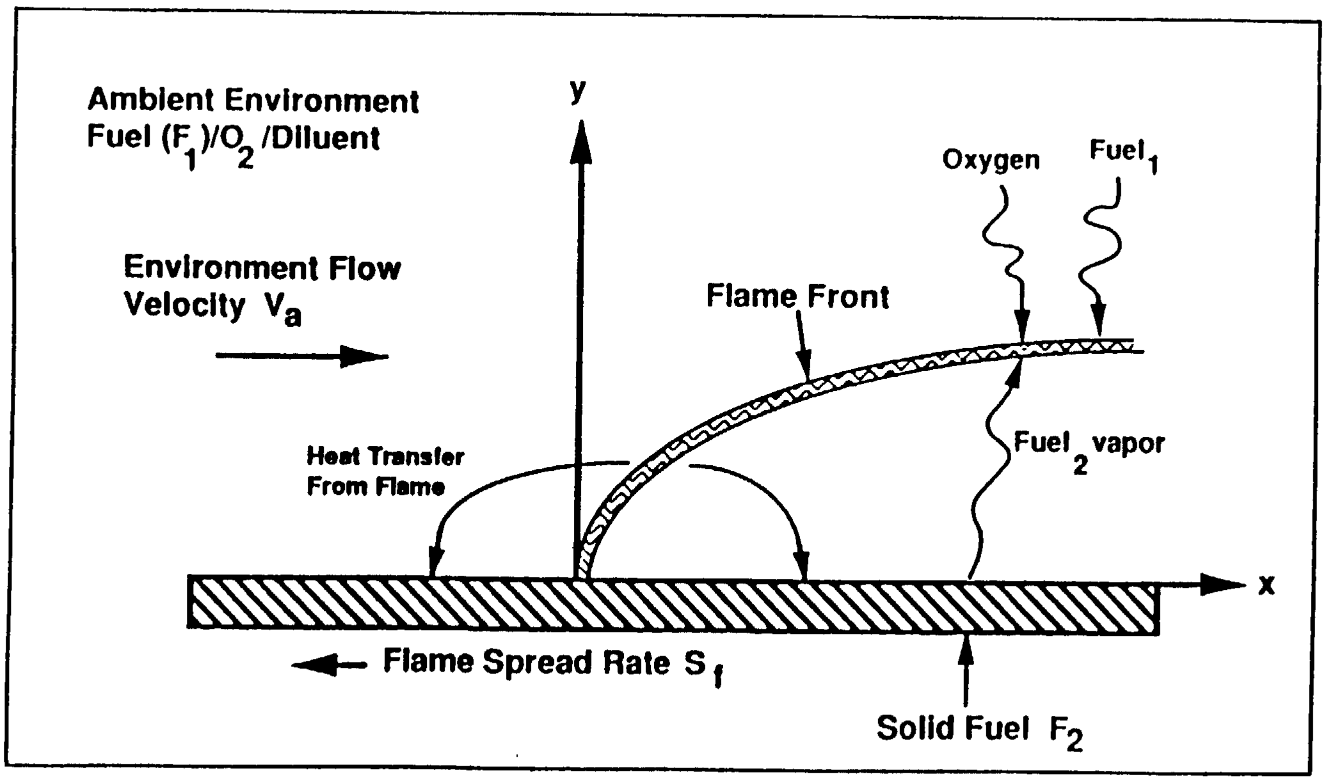


Figure 1. Flow Configuration for Flame Spread Problem

Flame spread theory - predictions

- $S_f \sim Y_{ox}$ or χ_{ox} (oxidant mass or mole fraction in atmosphere)
- $S_f \sim (\rho_s \tau_s)^{-1}$ (fuel bed mass per unit area)
- S_f is independent of pressure
- Atmosphere affects S_f directly through λ_g and indirectly through effect of $C_{p,g}$ and partial premixing on T_f
- No extinction predicted since models assumed infinite reaction rate and no heat losses
- Models assume Lewis number = 1

$$Le \equiv \frac{\text{Thermal diffusivity of atmosphere}}{\text{Mass diffusivity of } O_2 \text{ into atmosphere}}$$

...but Le is affected by diluent type

Diluent	*Le*
He	1.58
Ne	1.43
Ar	1.04
N_2	0.87
CO_2	0.57
SF_6	0.27

Objectives

- Study the effect of
  - Pressure
  - $(\rho_s \tau_s)^{-1}$ (fuel bed mass per unit area)
  - Oxidant mass fraction (Y_{ox}) or mole fraction (χ_{ox})
  - Diluent type
  - "Partial premixing"

  on

  - Flame spread rate
  - Flame temperature
  - Visible flame structure

  and compare with theoretical predictions

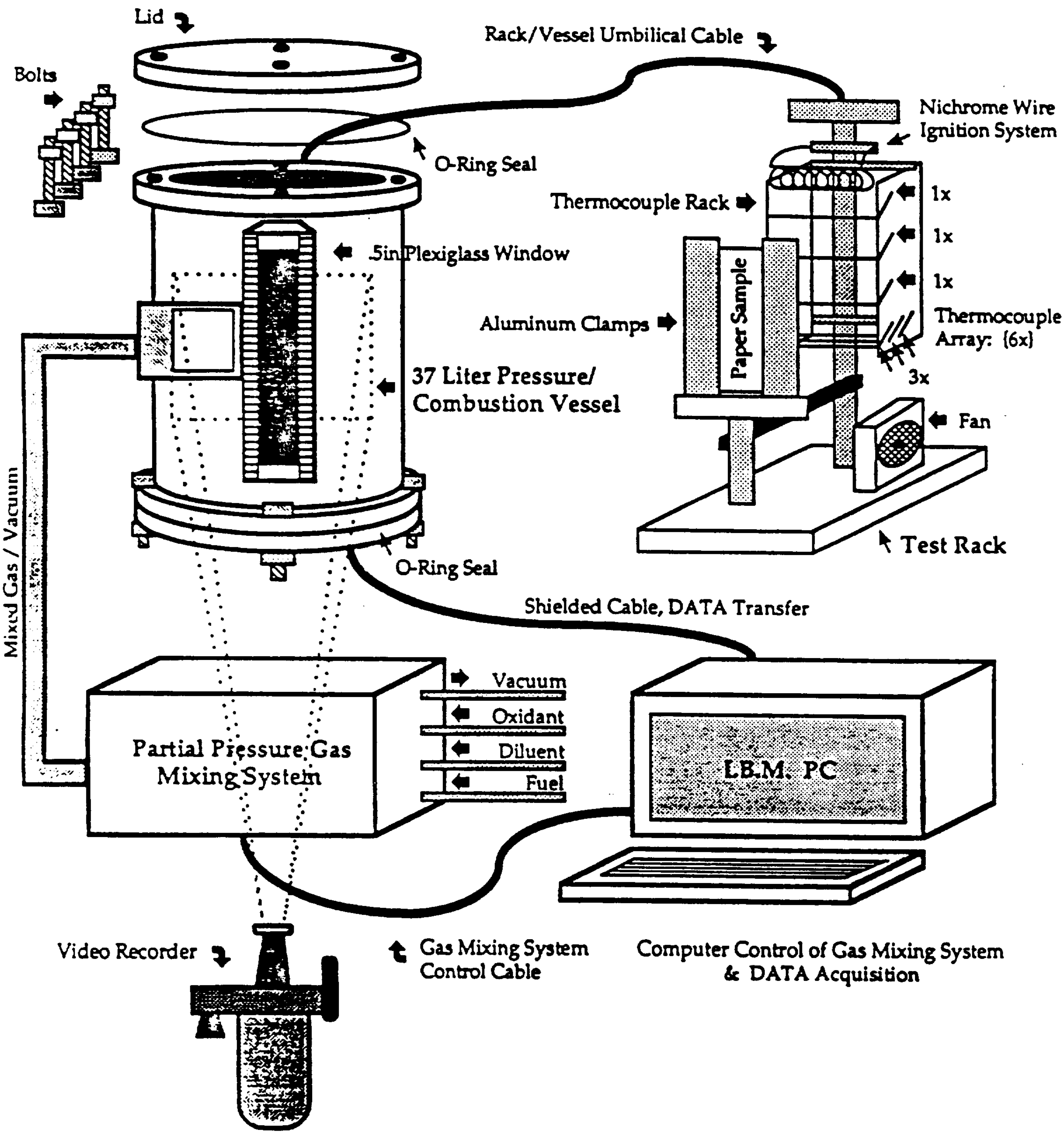
- Assess the implication of these results to fire safety applications

P. Ronney, Princeton Univ

P. Ronney, Princeton University

Approach

- Thin cellulose samples
- Downward propagation (spread opposing flow due to buoyancy)
- Controlled atmosphere in 37 liter chamber, partial pressure gas mixing
  - He, Ne, Ar, N_2, CO_2, SF_6 diluents in O_2
  - 0.4 to 2.3 atm
- 5 cm wide samples, clamped to inhibit edge-burning effects
- Array of 0.002" thermocouples to measure temperatures (radiative correction applied)
- Ignition by coiled nichrome wire coated with nitrocellulose
- Record video and thermocouple data



Block Diagram of Experimental Apparatus

P. Ronney, Princeton Univ

Results - spread rates

- $S_f \sim Y_{ox}$ and χ_{ox} except near extinction limit
- S_f is independent of pressure except near limits
- $S_f \sim (\rho_s \tau_s)^{-1}$; $dS_f/d\chi_{ox} \sim (\rho_s \tau_s)^{-1}$
- All qualitatively consistent with simple theory

Figure 2. Flame spread rates vs. oxygen mole fraction for various diluents at 1 atm total pressure. (a) Fuel bed thickness =0.0065 in

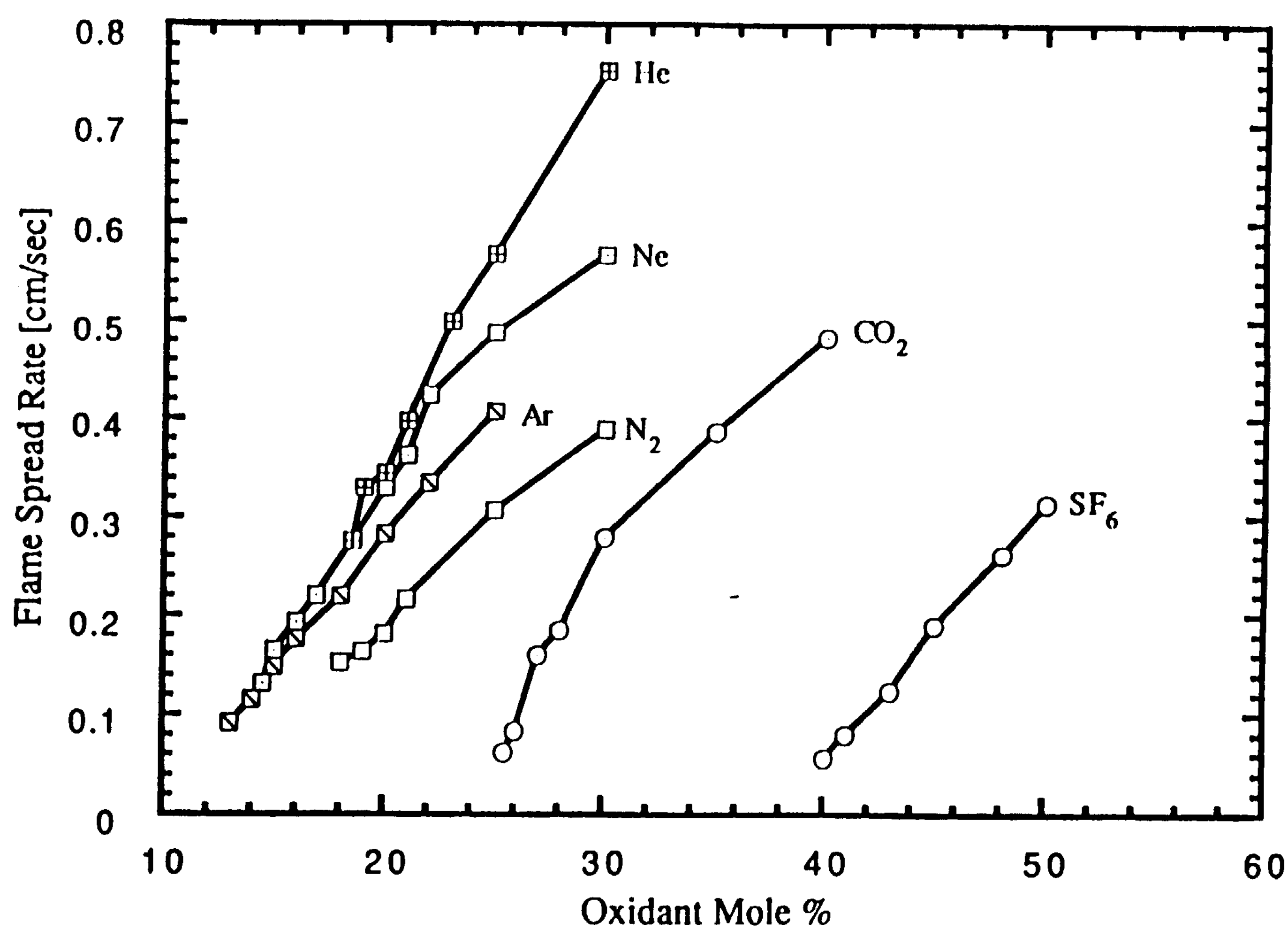


Figure 3. Pressure effects on flame spread rates in various O2-diluent atmospheres.

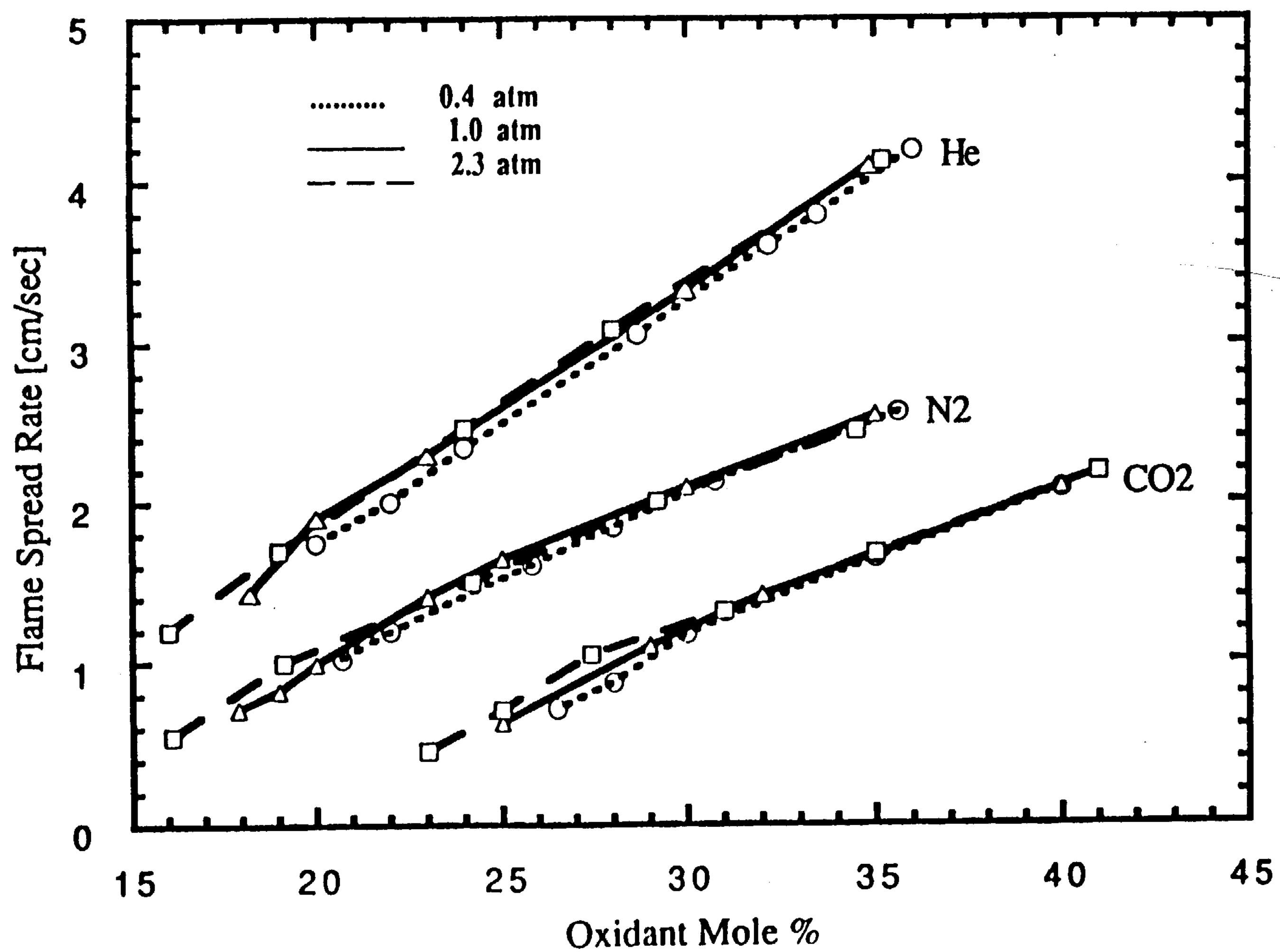


Figure 4. Effect of mass of fuel bed unit area ($\rho_s \tau_s$) on flame spread rates at 1 atm in various O_2-diluent mixtures

(a) S_f versus $\phi r_s \tau_s$ for various diluents and χ_{O2}.

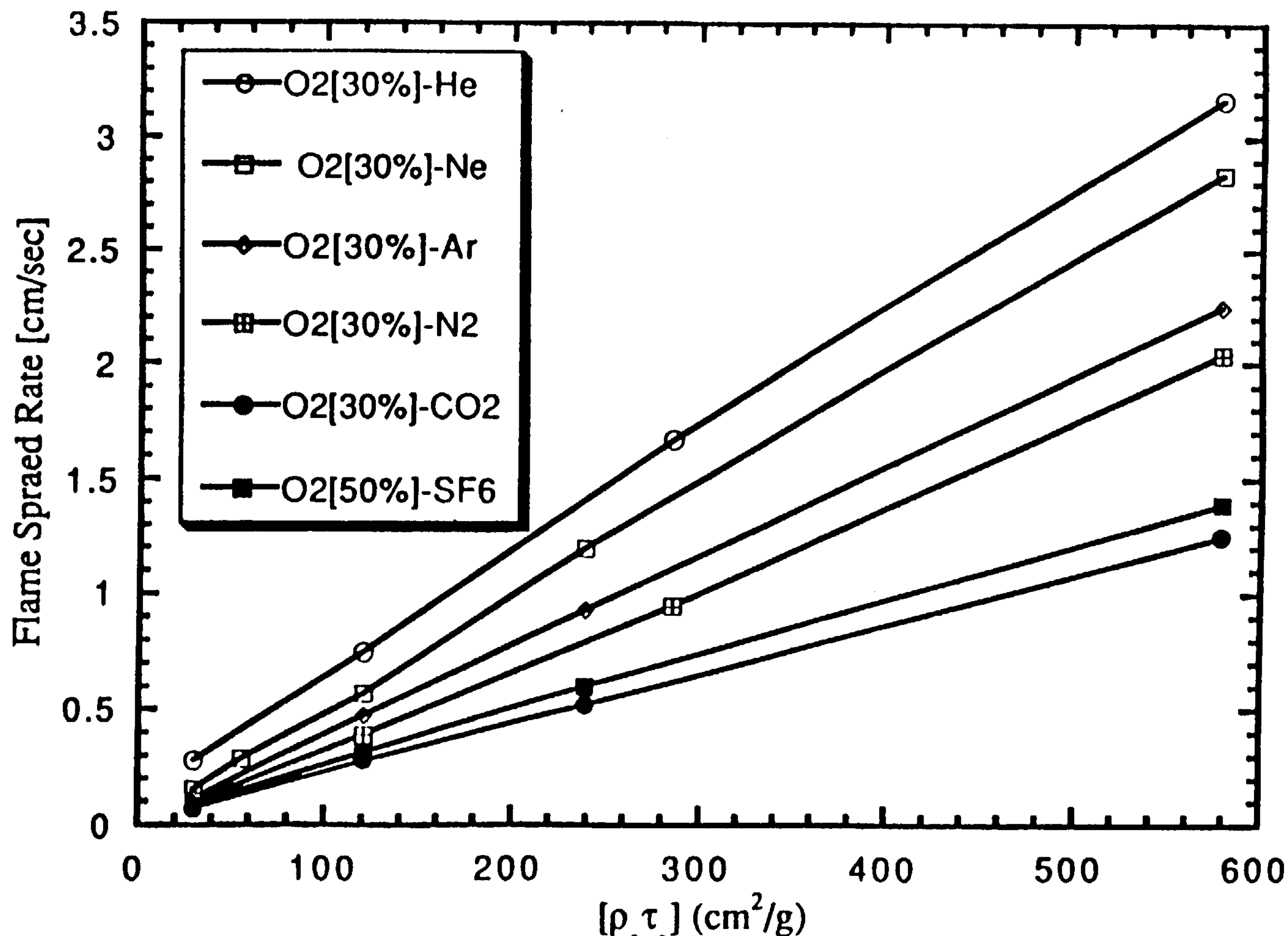
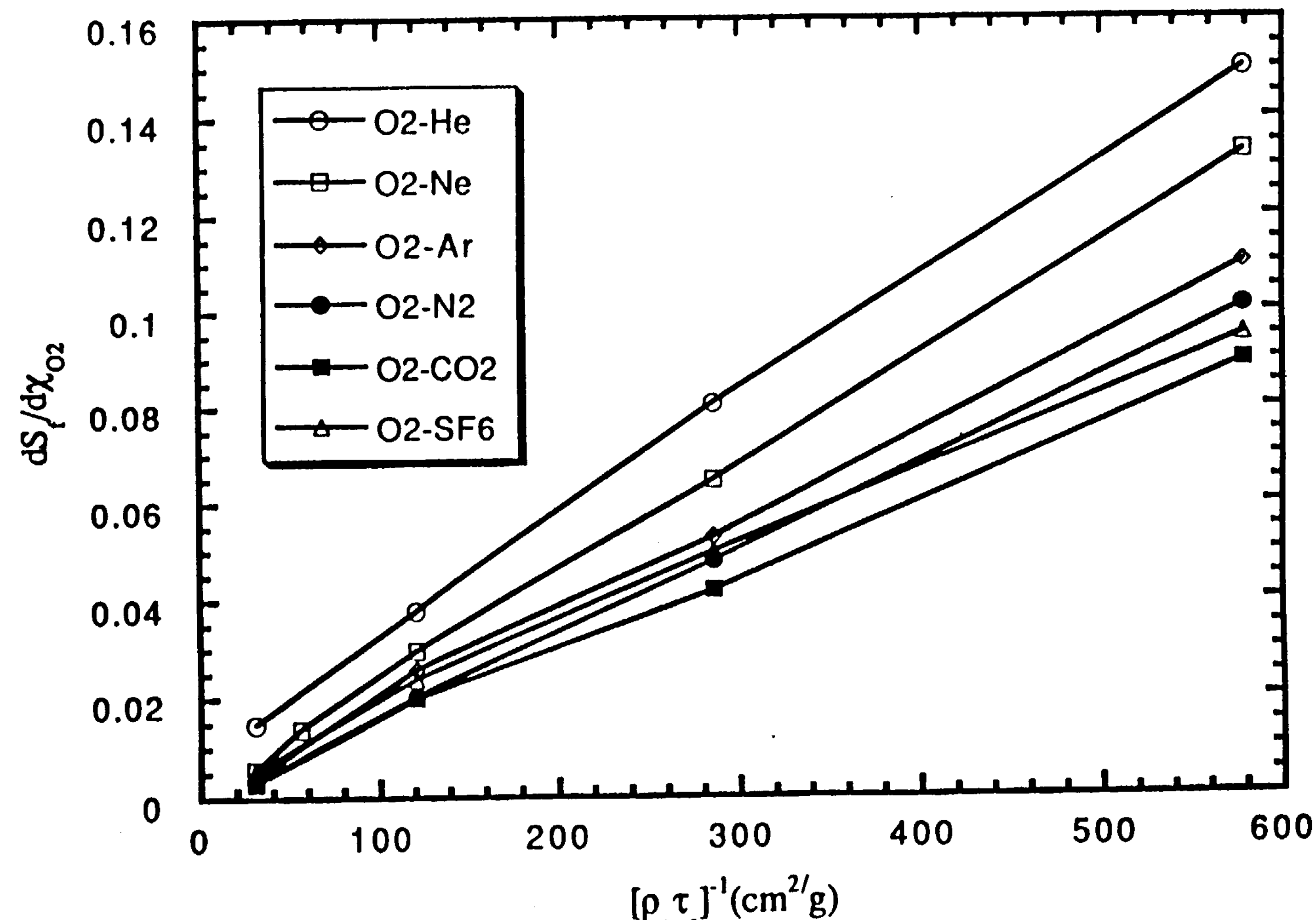


Figure 4. (b) $dS_f/d\chi_{O2}$ versus $(\rho_s\tau_s)$ for various diluent and χ_{O2}



Results - spread rates (comparison w/ theory)

- Evaluate λ_g, $C_{p,g}$, Le using ambient compositions but mean temperature (Wichman & Williams, 1983)
- Theoretical results systematically too high/low when Le > 1 / Le < 1
- Agreement markedly improved if $S_f \rightarrow S_f/Le$
- Justification: Law & Chung (1982), nonpremixed *gaseous* flame, small convective flux normal to front:

  Same result as Le =1 but with $Y_{ox} \rightarrow Y_{ox}/Le$

  $\therefore\ T_{f(Le\neq1)} - T_v \approx (T_{f(Le=1)} - T_v)/Le$

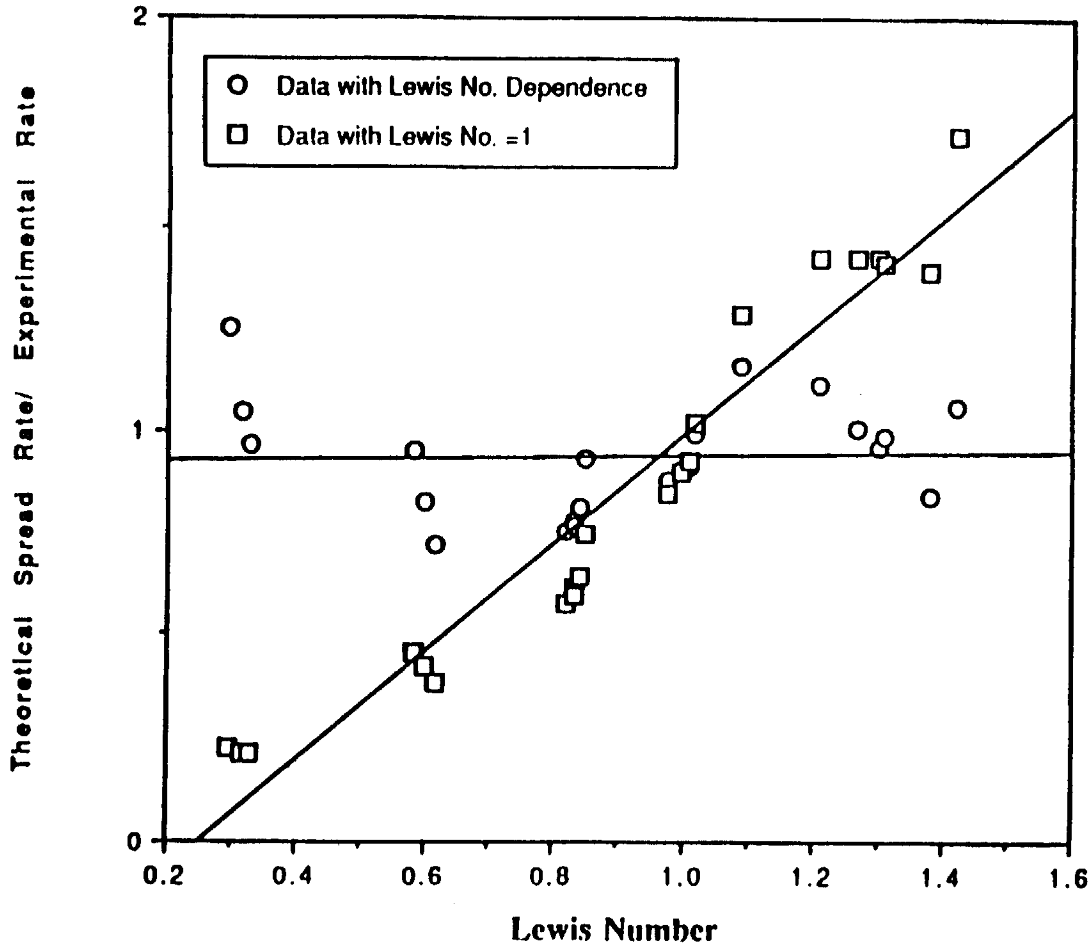
  $\therefore\ S_{f(Le\neq1)} \approx S_{f(Le=1)}/Le$

- Heuristic argument supported (almost) by more rigorous analysis (Greenberg & Ronney, 1991) - also shows *fuel* Le does not affect T_f or S_f !!!

Comparison of flame spread rates with theory

Diluent	χ_{O_2}	Le	$\frac{S_f(ex)}{S_f(th)}$	$\frac{S_f(ex)}{S_f(th)/Le}$
He	0.200	1.373	0.584	0.802
Ne	0.200	1.253	0.706	0.882
Ar	0.180	0.981	1.076	1.056
N_2	0.200	0.813	1.338	1.088
CO_2	0.300	0.564	2.177	1.228
SF_6	0.440	0.311	4.479	1.393
MEAN			1.727	1.075
STD. DEV.	(% of mean)		84.7%	20.3%

- **All data shown are conditions far removed from the flammability limits**



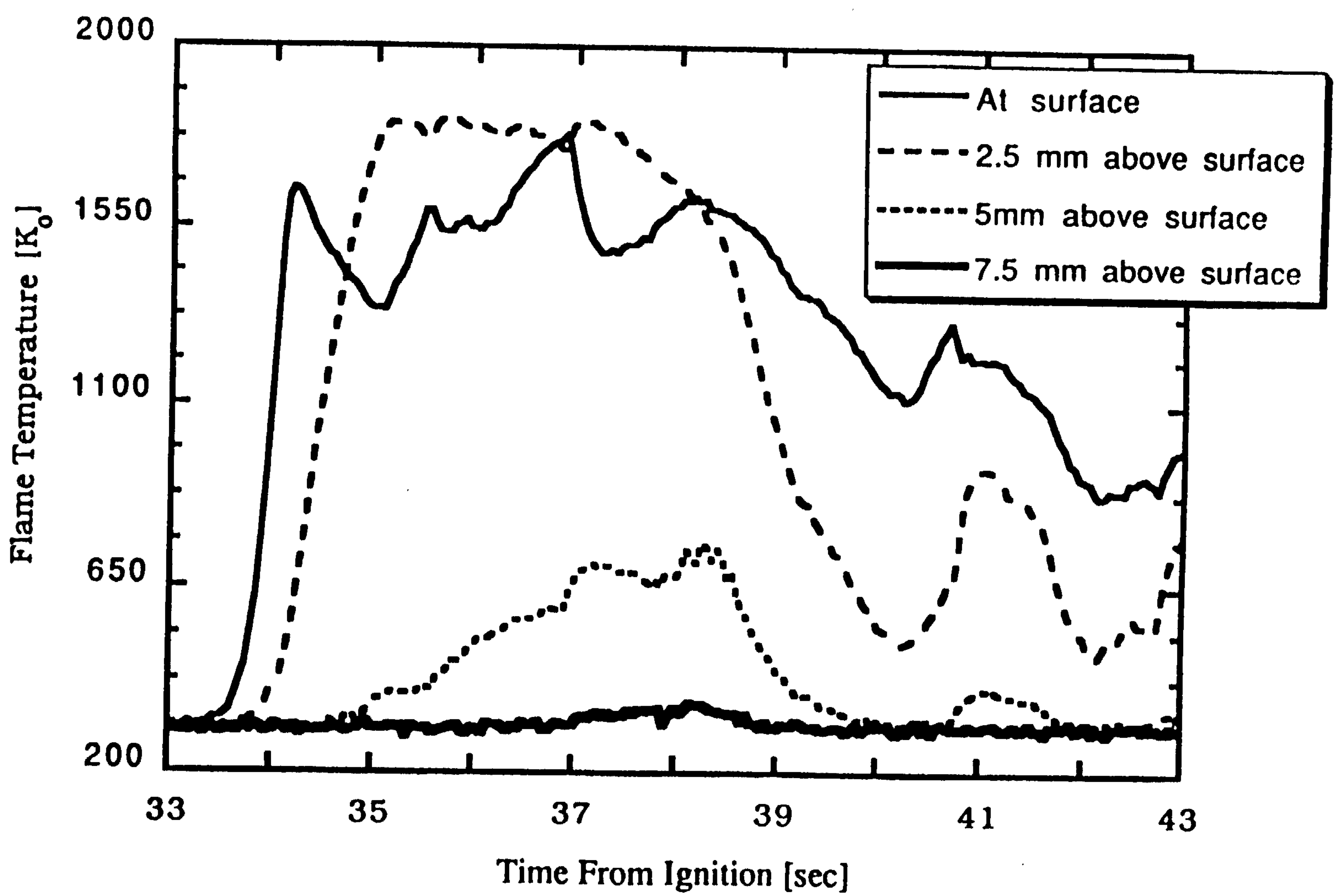
Comparison of Experimental and Theoretical Flame Spread Rates as a Function of Lewis Number

Results - flame temperatures

- $Le \neq 1$ theory predicts effect of Le on T_f
- Test - O_2/He, O_2/Ne, O_2/Ar atmospheres at same χ_{O2}
  - $Le = 1$ theory predicts all have same T_f
  - $Le \neq 1$ theory predicts strong influence of Le onT_f
  - Experimental results show signficant improvement in comparison with theory when $Le \neq 1$ theory applied

Diluent	Le	T_f ($Le = 1$) (no dissoc.)	T_f ($Le \neq 1$) (no dissoc.)	T_f ($Le \neq 1$) (w/ dissoc.)	Expt.
He	1.37	2601K	1757	1747	1700
Ne	1.25	2601K	2089	2039	2000
Ar	0.98	2601K	2691	2397	2100

Figure 5. (c) O_2-Ar atmosphere [1 atm], $\chi_{O2}=0.2$.



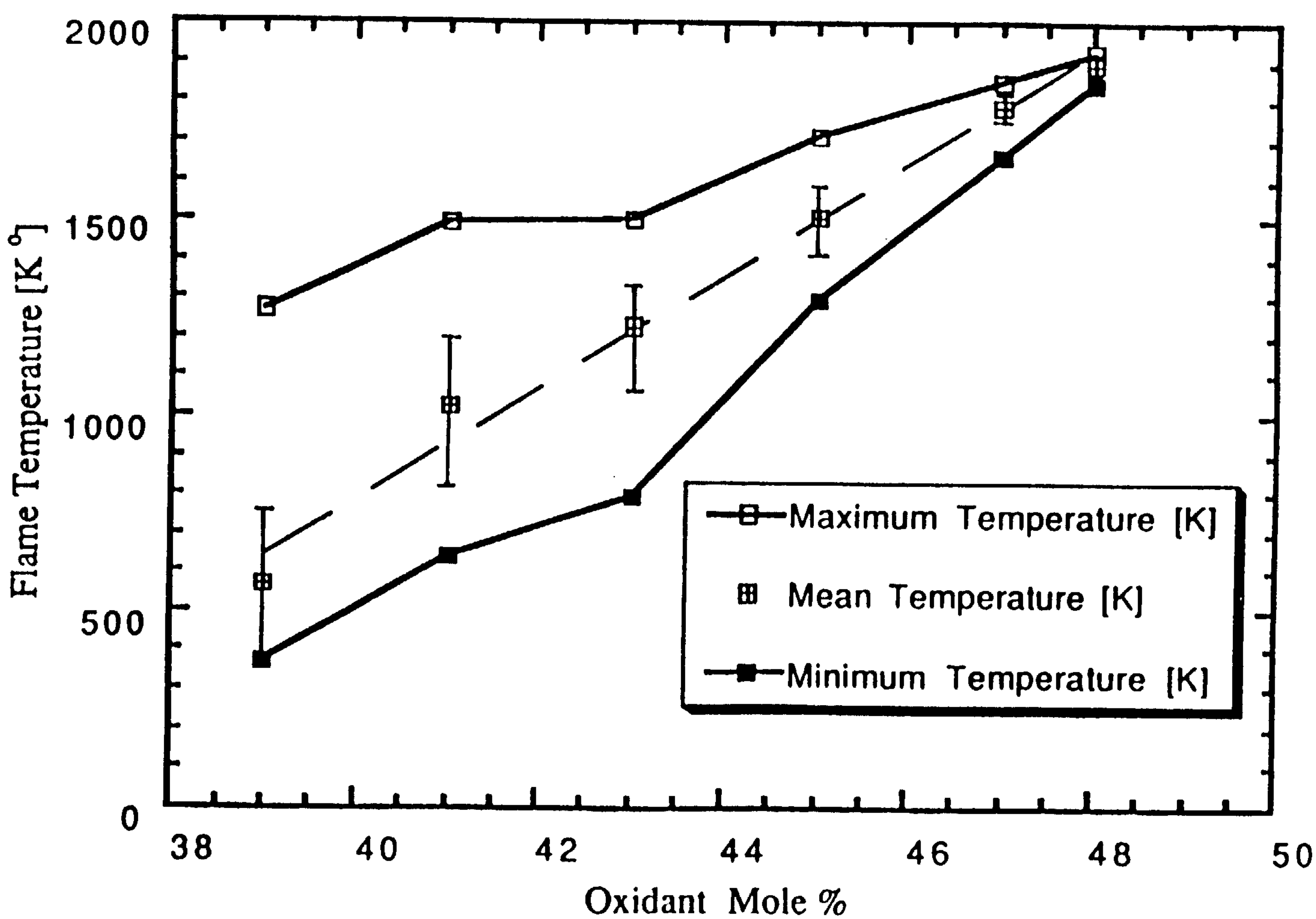
Results - visible flame structure

- New phenomenon observed in O_2/CO_2 and O_2/SF_6 mixtures - *cellular flame spread* (?!?)
    - Only seen near extinction limit
    - Most pronounced at high P and in thin fuel beds
    - Greater variability of measured T_f in cellular flames

- Proposed mechanism
    - Cellular structure normally associated with premixed flames due to diffusive-thermal instability when $Le < 1 - 2/\beta$ (β = non-dim. activation energy)
    - Non-premixed flames: partial premixing occurs near extinction limits; produces mixed but not burned gases (Liñán, 1974)
    - Near extinction, partially premixed regions may be subject to diffusive-thermal instability similar to premixed flames
    - Supported by observations: cells only near limit, only for $Le < 1$
    - Supported by recent experiments in *gaseous* slot-burner

P. Ronney, Princeton University

Figure 7. Temperature characteristics of spreading cellular flame.
(b) Peak temperature as afunction of χ_{O2} for O_2-SF_6 at 1 atm



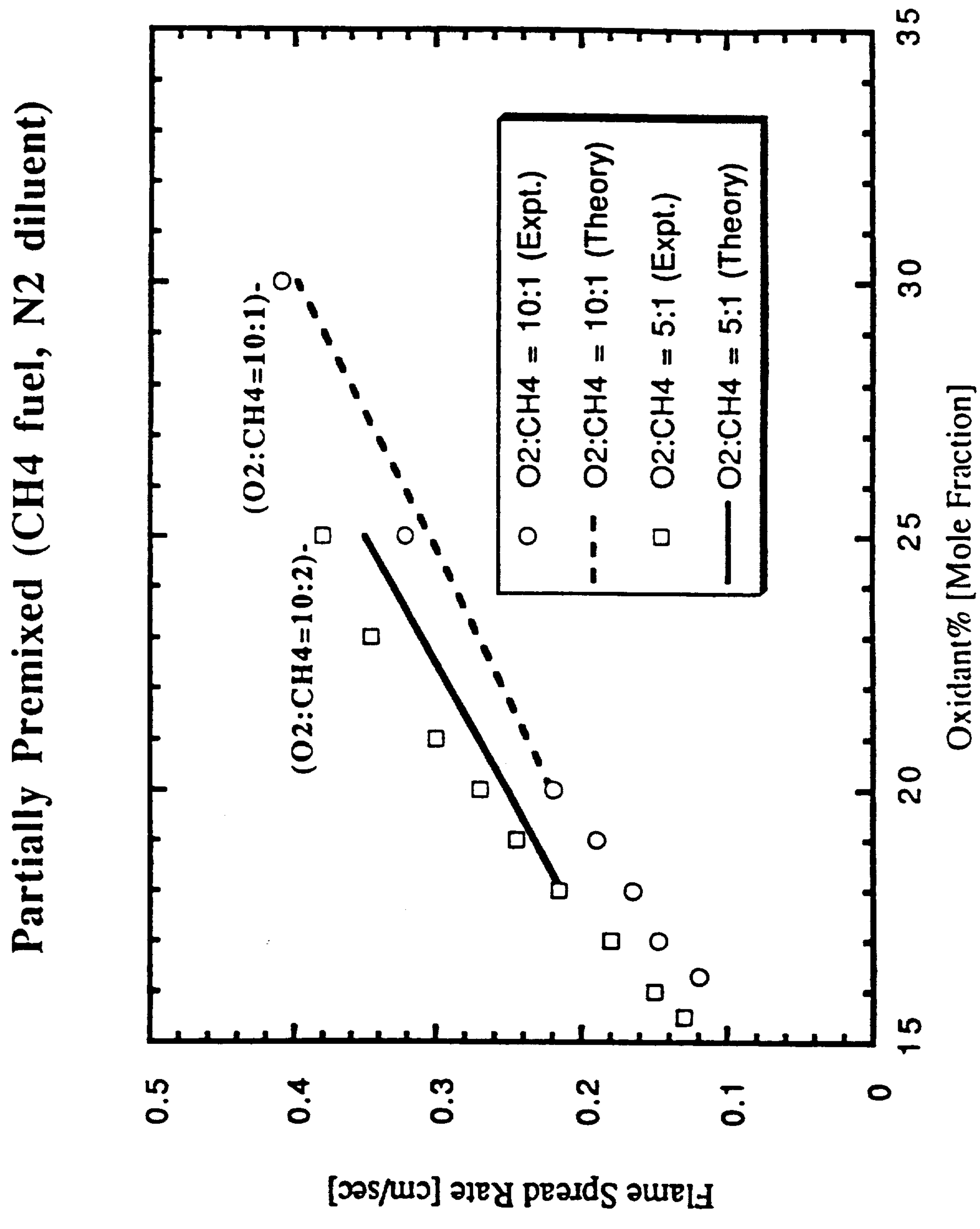
"Partially premixed" flame spread

- **Experiments in atmospheres with CH_4, C_3H_8, CO fuel added show pronounced effect on S_f *away from limits***

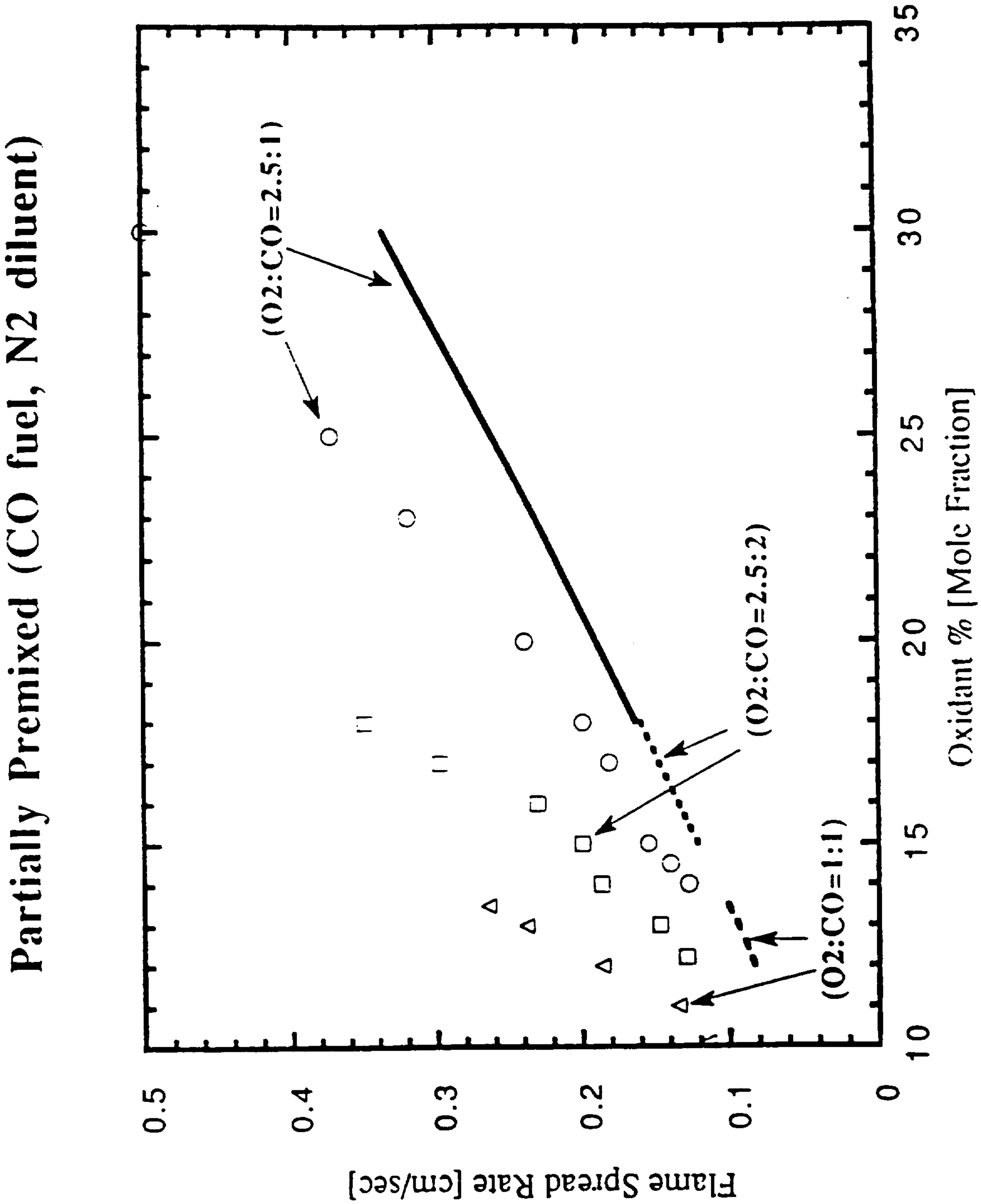
  ... but "partial premixing" has little effect on % O_2 at limit (except for CO fuel) or S_f *at limit*

- **Theory (Greenberg & Ronney, 1991) agrees with experiments only for low fuel concentrations**

- **Need improved theory to account for possibility of <u>two flame fronts</u> - one for each fuel**



Partially Premixed (CH4 fuel, N2 diluent)
Flame Spread Rate [cm/sec]
Oxidant% [Mole Fraction]
0
0.1
0.2
0.3
0.4
0.5
15
20
25
30
35
(O2:CH4=10:1)-
(O2:CH4=10:2)-
O2:CH4 = 10:1 (Expt.)
O2:CH4 = 10:1 (Theory)
O2:CH4 = 5:1 (Expt.)
O2:CH4 = 5:1 (Theory)



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Extinction criteria

- Empirical observation: <u>all</u> extinction data can be correlated within ± 25% by

$$S_f \text{ (at limit)} \sim \left(\frac{g\,\lambda_g}{\rho_g C_{p,g}}\right)^{1/3} \frac{(\rho_s \tau_s)_{ref}}{(\rho_s \tau_s)}$$

for all diluents, pressures, fuel thicknesses, and gaseous fuels !!!

- Strongly suggests buoyancy-induced "blow-off" limit

... but why isn't a Damkohler number present to account for effects of diluent, Le, gaseous fuel, etc. on chemical reaction rate via T_f ???

Application to fire safety issues

- **SF_6 is best extinguishant on mole basis despite low Le - important when pressure or volume of stored agent is critical**

- **He is best extinguishant (by far) on mass basis and very good on mole basis because of high Le**

Diluent	*Le*	χ_{O2} at limit	χ_{dil}/χ_{O2} at limit	Y_{dil}/Y_{O2} at limit
He	1.58	0.178	4.62	0.58
Ne	1.43	0.141	6.09	3.84
Ar	1.04	0.126	6.94	8.66
N_2	0.87	0.175	4.71	4.13
CO_2	0.57	0.250	3.00	4.13
SF_6	0.27	0.392	1.55	7.08

Application to fire safety issues (continued)

- **Helium has other advantages:**
  - **Guaranteed inert**
  - **Aids cooling of electronics**
  - **Water-solubility less than N_2 - less pre-breathing needed before EVA**
- **... but also has disadvantages**
  - **Leaks easier than N_2**
  - **"Mickey Mouse" effect**
- **Helium *even better* fire-safe atmosphere for "thermally thick" fuels; de Ris:**

$$S_f \sim \frac{\lambda_s \rho_s C_{p,s}}{\lambda_g \rho_g C_{p,g}} \frac{T_f - T_v}{T_v - T_0} V_g \,; \quad V_g \sim \left(\frac{g\,\lambda_g}{\rho_g C_{p,g}}\right)^{1/3} + \text{forced convection}$$

- both Le effects on T_f <u>and</u> high λ_g lower S_f

- **"Straw-man" suggestion: employ $\approx$ 18% O_2 / 82% He atmosphere at $P \approx 15$ psia**

P. Ronney, Princeton Univ

P. Ronney, Princeton University

Summary and Conclusions

- Experiments on flame spread over thin solid fuels in a variety of O_2-diluent-fuel atmospheres show
  - Pressure and fuel bed thickness effects as expected
  - Evidence of oxygen Lewis number effects not previously reported
    - Spread rates
    - Flame temperatures
    - Cellular flames

    ... which could alter selection of atmospheres & extinguishants
  - Flame spread can be much faster when gaseous fuel is present, but improved model is needed
- Future work
  - Study of extinguishment mechanisms - buoyancy-induced "blow-off", heat loss
  - Upward flame spread

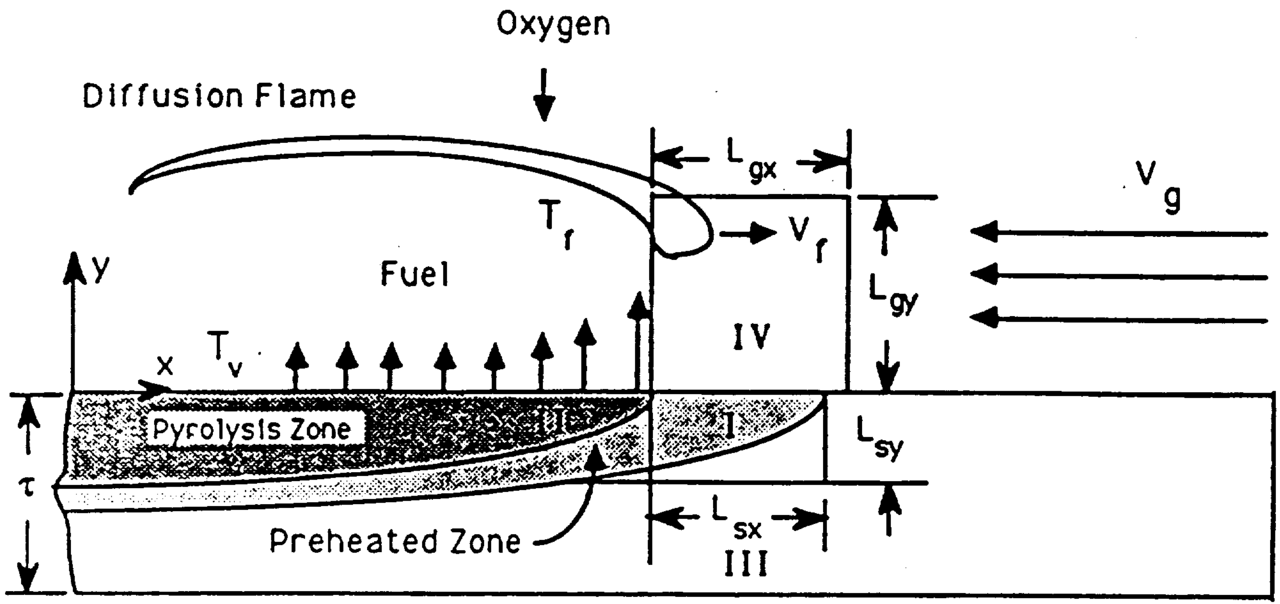
THE SOLID SURFACE COMBUSTION EXPERIMENT (SSCE)

SCIENTIFIC OBJECTIVES:

Determine the mechanisms of gas-phase flame spread over solid-fuel surfaces in the absence of any buoyancy-induced or externally-imposed gas-phase flow.

Improve the fire-safety aspects of space travel.

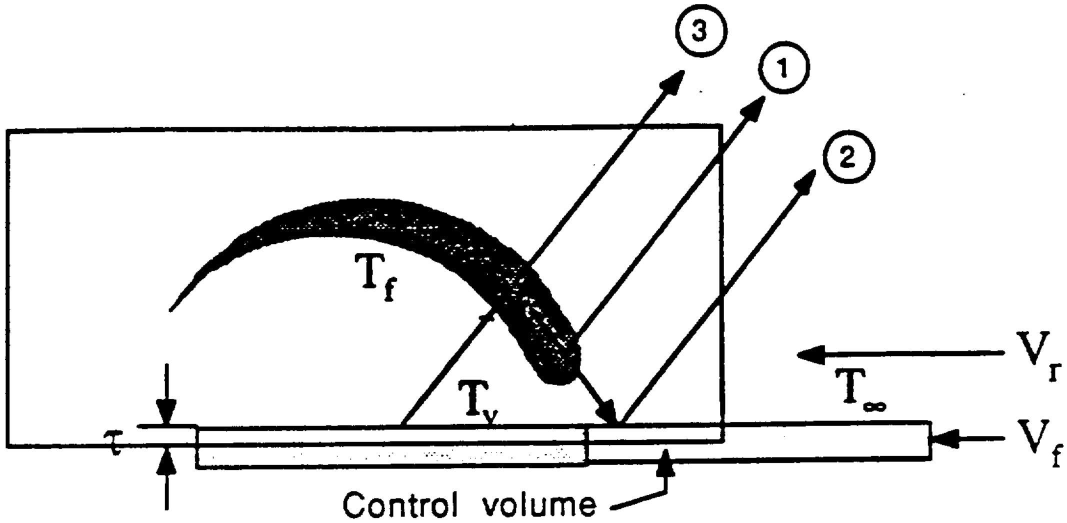
R. Altenkirch, Mississippi State Univ.



Oxygen
Diffusion Flame
L_{gx}
V_g
T_f
V_f
y
Fuel
L_{gy}
x
T_v
IV
Pyrolysis Zone
II
I
L_{sy}
τ
Preheated Zone
L_{sx}
III

Fig. 1

Flame Cooling through Radiative Losses



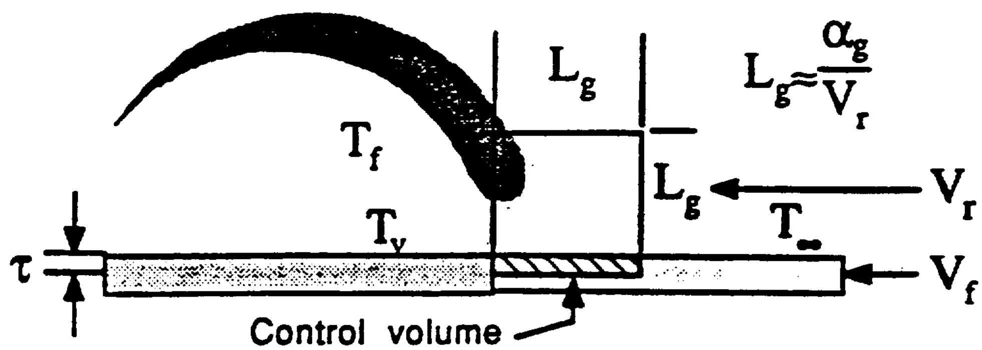
$$\dot{Q}'_{loss} \approx \dot{Q}'_{gbr}(1\text{-}f) + \dot{Q}'_{gbr} f(1\text{-}\alpha) + \dot{Q}'_{ser}$$

(1) (2) (3)

gbr = gas → boundry
f = fraction lost to fuel

R. Altenkirch, Mississippi State Univ.

Radiative Effects on Spread Rate



$$\rho_s C_s \tau V_f (T_v - T_\infty) = \dot{Q}'_{gsc} + \alpha \dot{Q}'_{gsr} - \dot{Q}'_{ser}$$

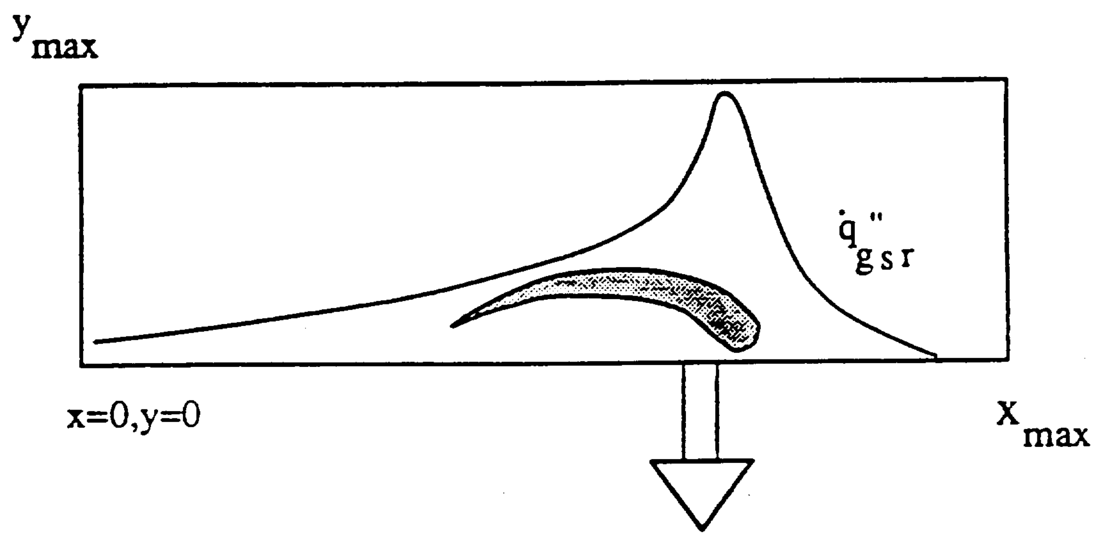
$$\dot{Q}'_{gsc} \approx \lambda_g (T_f - T_v)$$

$$\dot{Q}'_{ser} \approx \varepsilon\sigma(T_v^4 - T_\infty^4) L_g \qquad \dot{Q}'_{gsr} \approx f4a_P\sigma(T_f^4 - T_\infty^4)L_g^2$$

If only surface radiation is included,

$$V_f \approx V_{f0} - V_{f0} S_R \frac{T_v^4 - 1}{T_f - 1}, \text{ where } \quad S_R = \frac{\varepsilon\sigma T_\infty^3}{\rho_g C_g V_r}$$

Evaluation of Gas-to-Surface Radiation

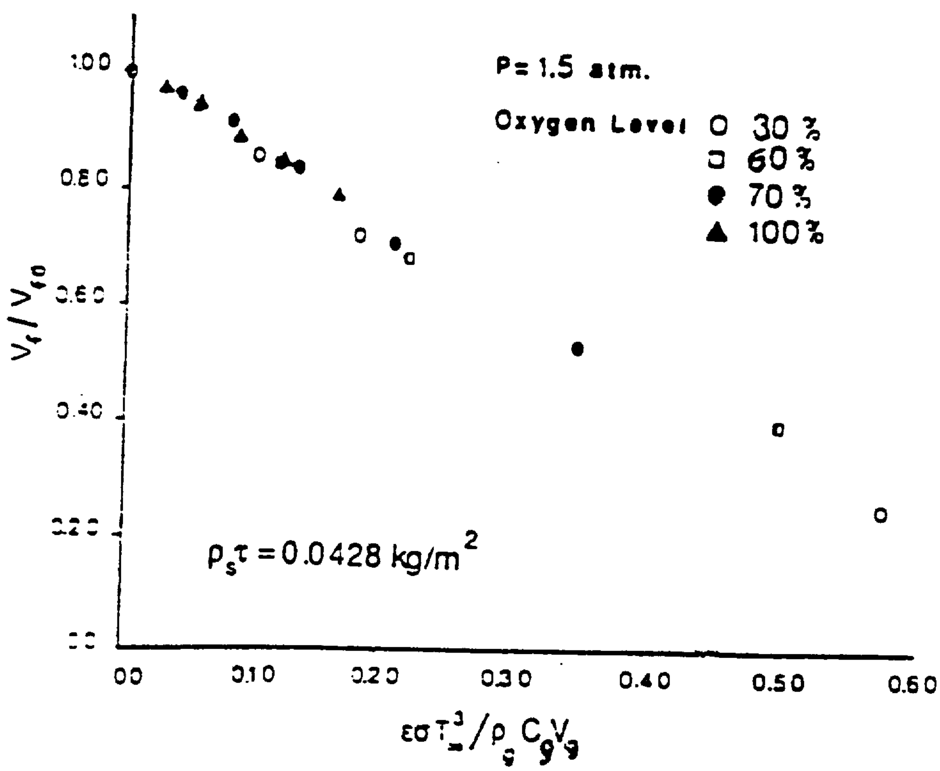


$$\dot{Q}'_{gsr} = \int_0^{x_{max}} \dot{q}''_{gsr}\,dx \ ; \qquad \dot{Q}'_{gbr} = \int_{boundary} \dot{q}''_{gbr}\,ds$$

$$f \equiv \frac{\dot{Q}'_{gsr}}{\dot{Q}'_{gbr}} \ ; \qquad \psi(x) \equiv \frac{\dot{q}''_{gsr}(x)}{\dot{Q}'_{gsr}}$$

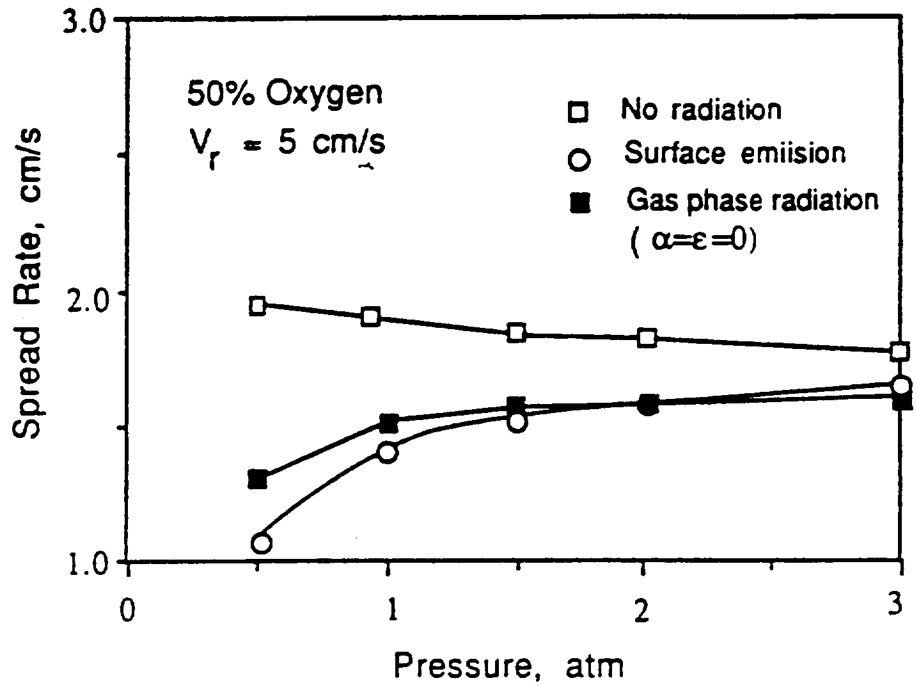
$$\therefore \quad \dot{q}''_{gsr}(x) = f\,\psi(x)\ 4a_p\sigma \iint (T^4 - T_\infty^4)\,dxdy$$

Surface Radiation Effect on Spread Rate

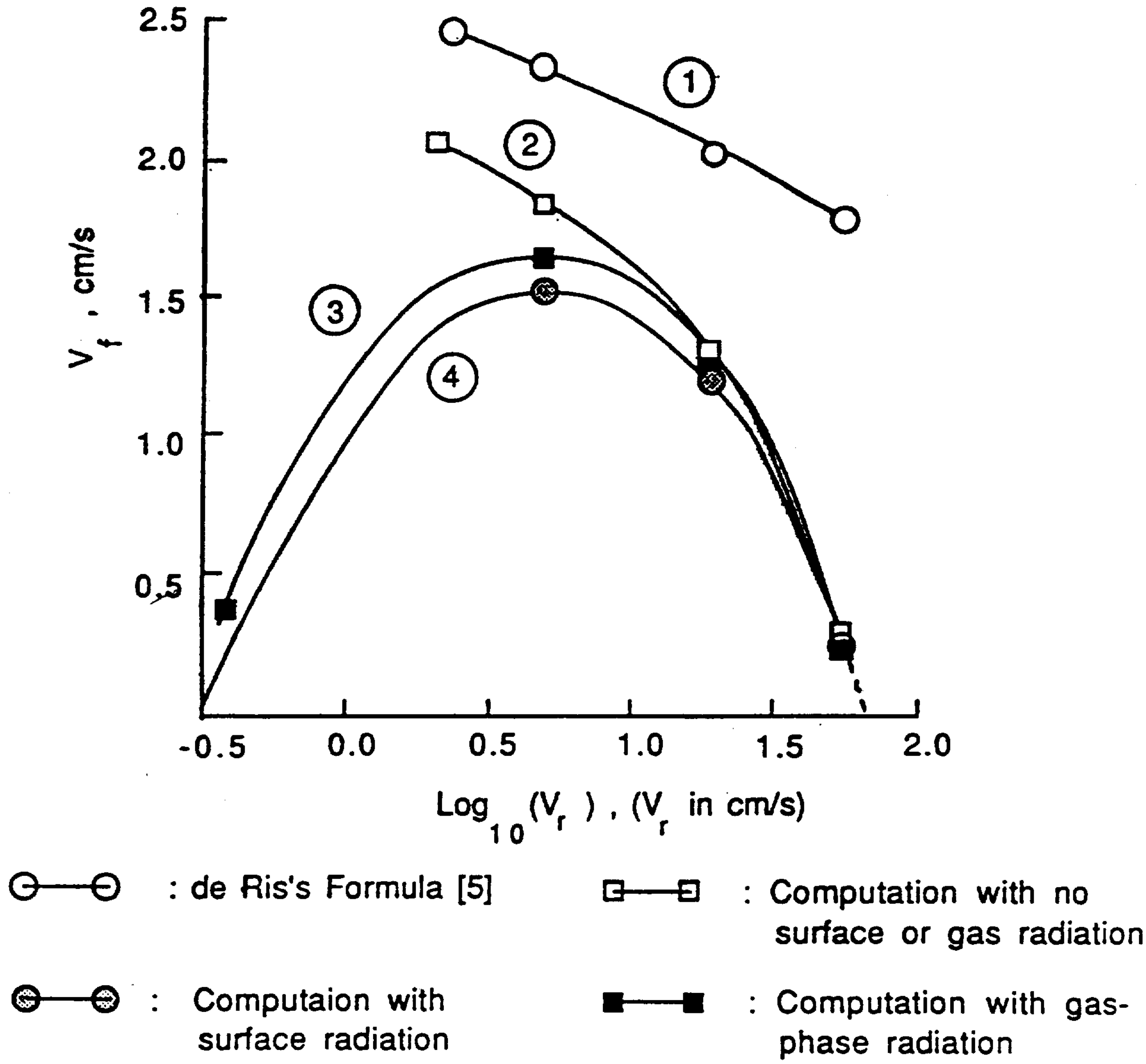


R. Altenkirch, Mississippi State Univ.

Effect of Ambient Pressure: Theory



R. Altenkirch, Mississippi State Univ.



2.5
2.0
1.5
1.0
0.5
V_f, cm/s
-0.5
0.0
0.5
1.0
1.5
2.0
$Log_{10}(V_r)$, (V_r in cm/s)
1
2
3
4
: de Ris's Formula [5]
: Computation with no surface or gas radiation
: Computaion with surface radiation
: Computation with gas-phase radiation

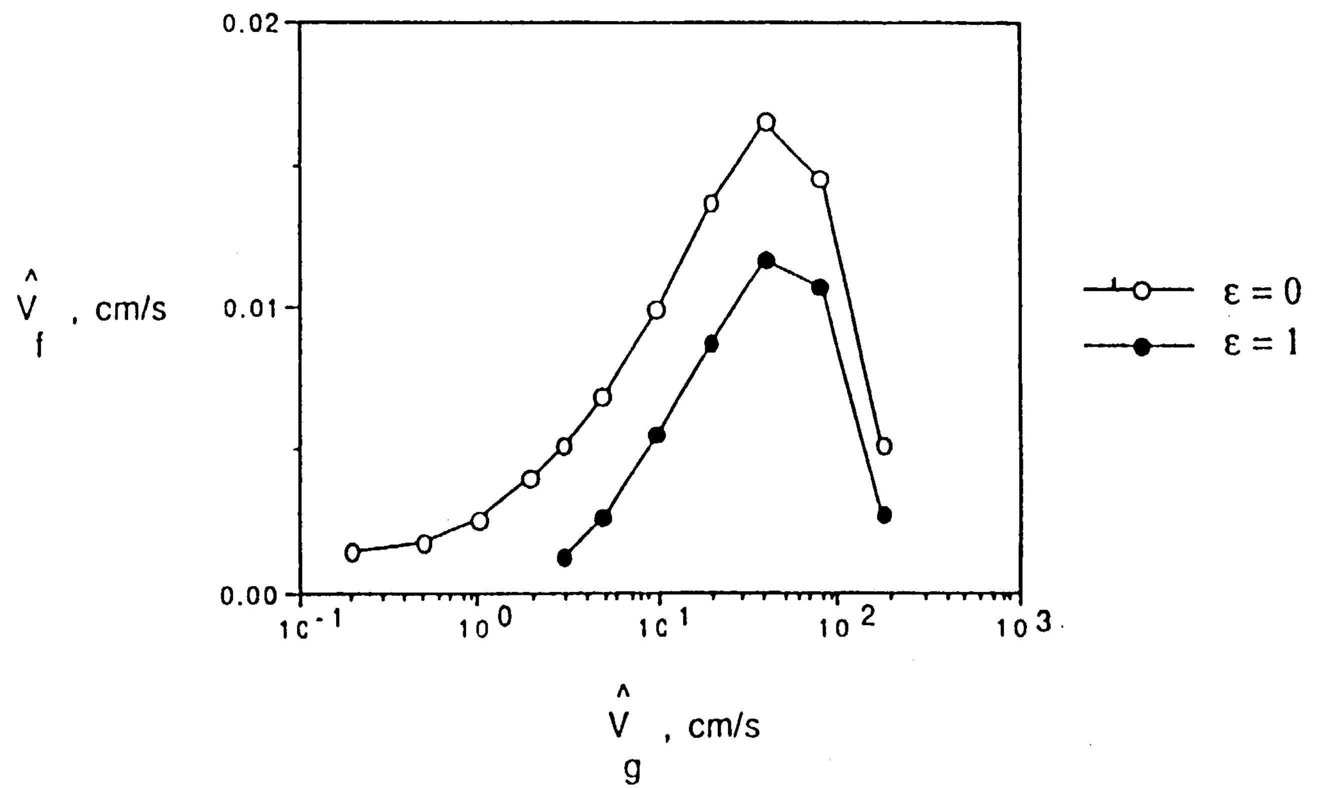
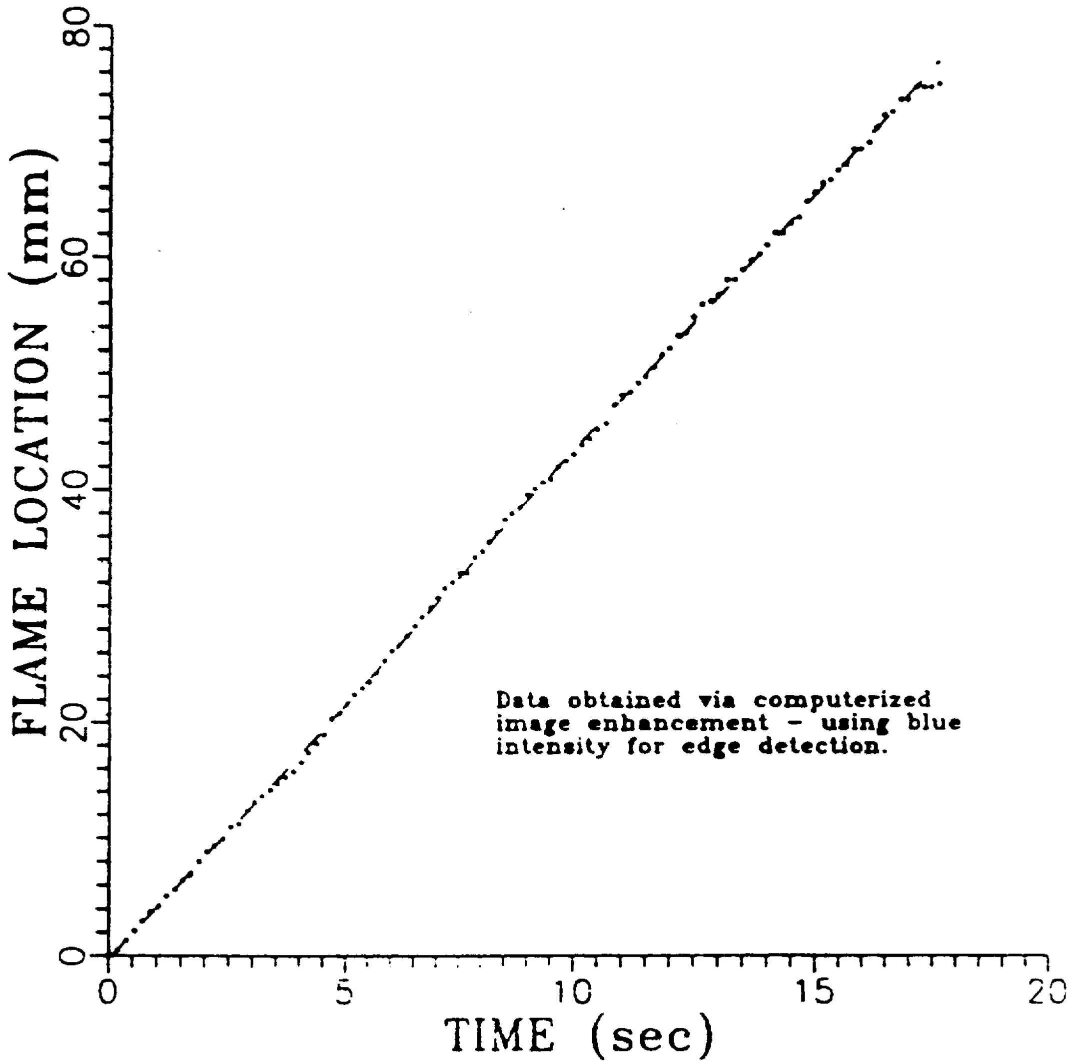


Fig. 15. Theoretical thermally thick spread rate as a function of forced opposing velocity, $\hat{V}_g$, at 50% O_2 in N_2 and 1 atm pressure for fuel surface emittance of zero and unity.



SSCE-STS-41:
ASHLESS FILTER PAPER
1:1 O_2:N_2 1.5 ATM

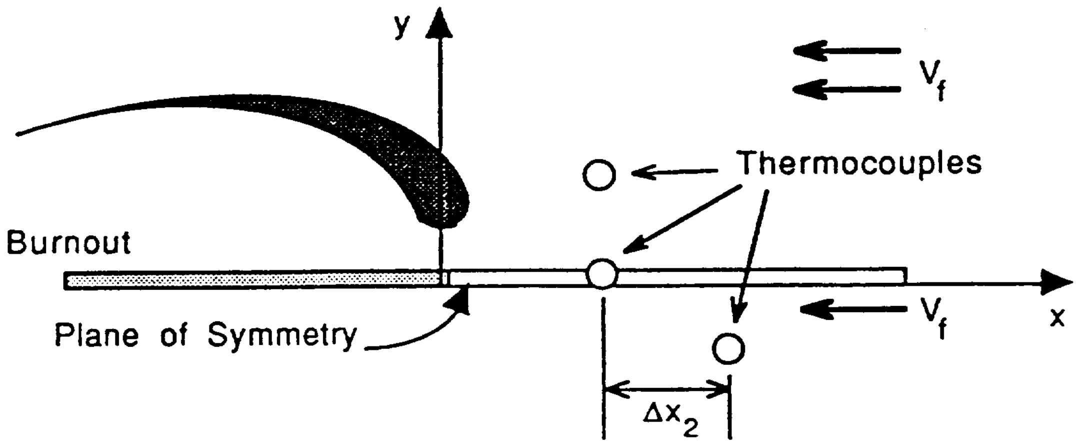
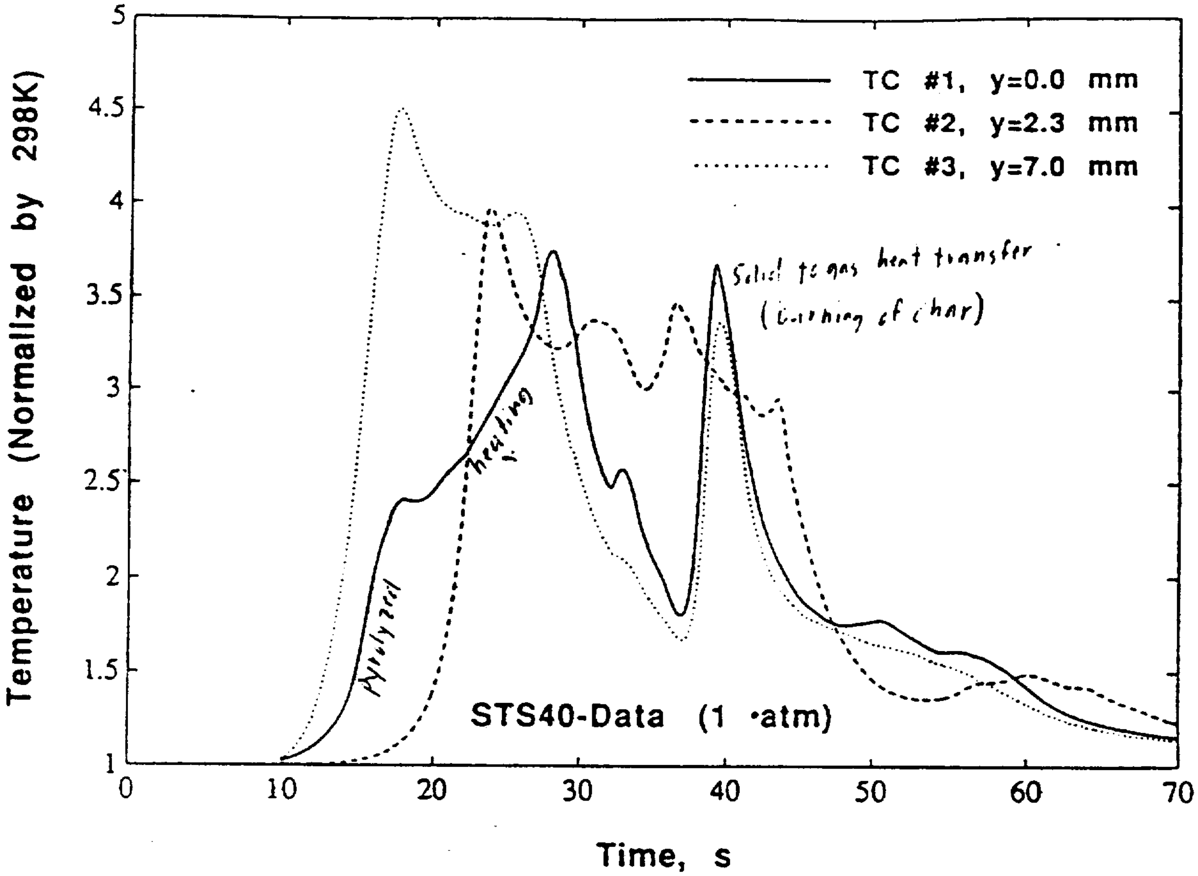
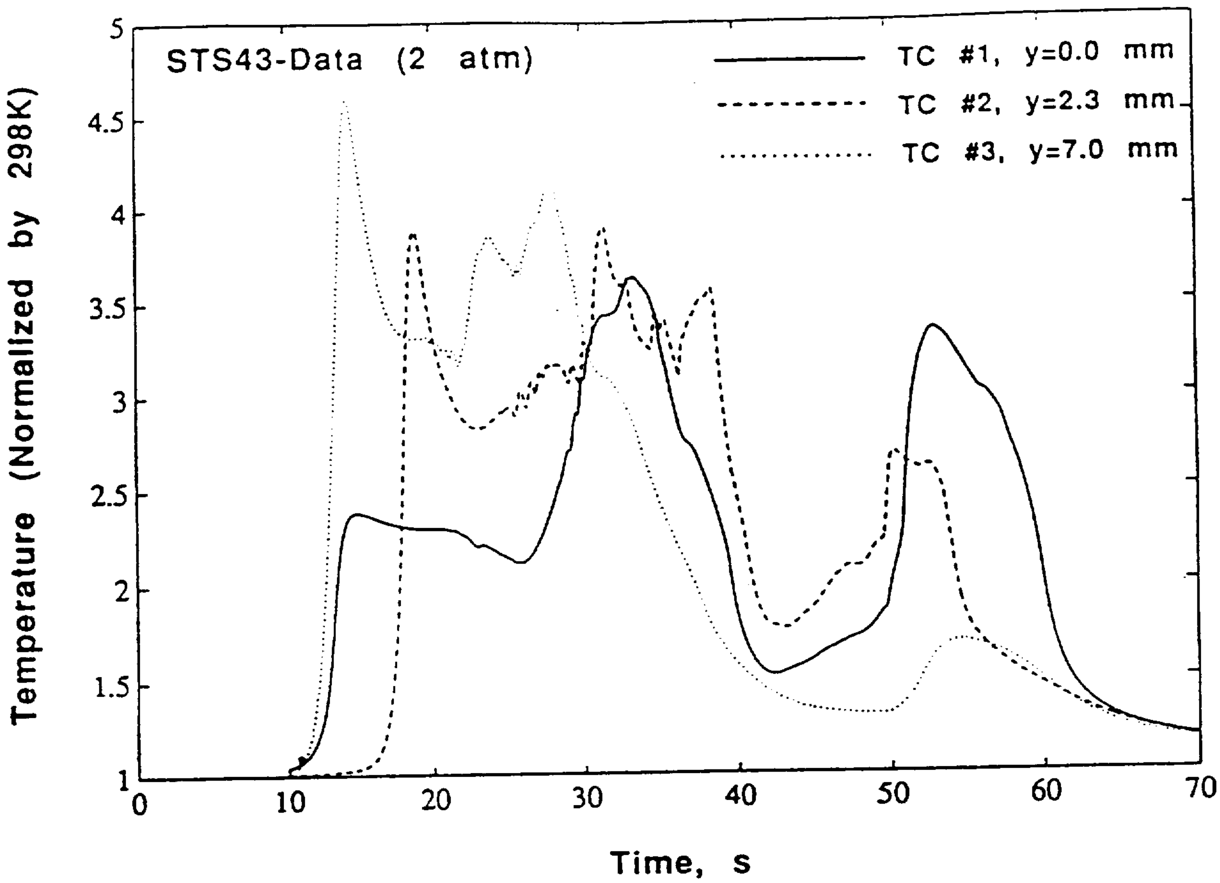
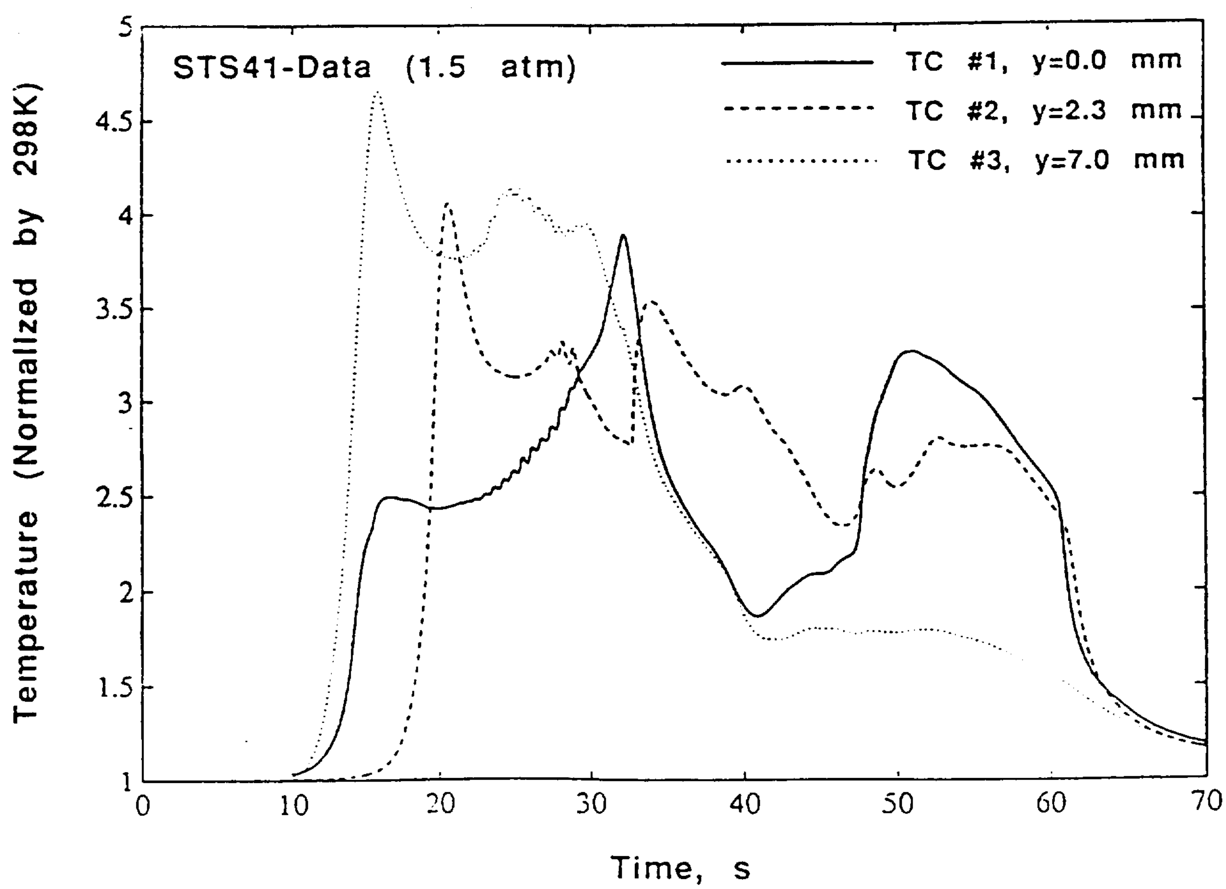


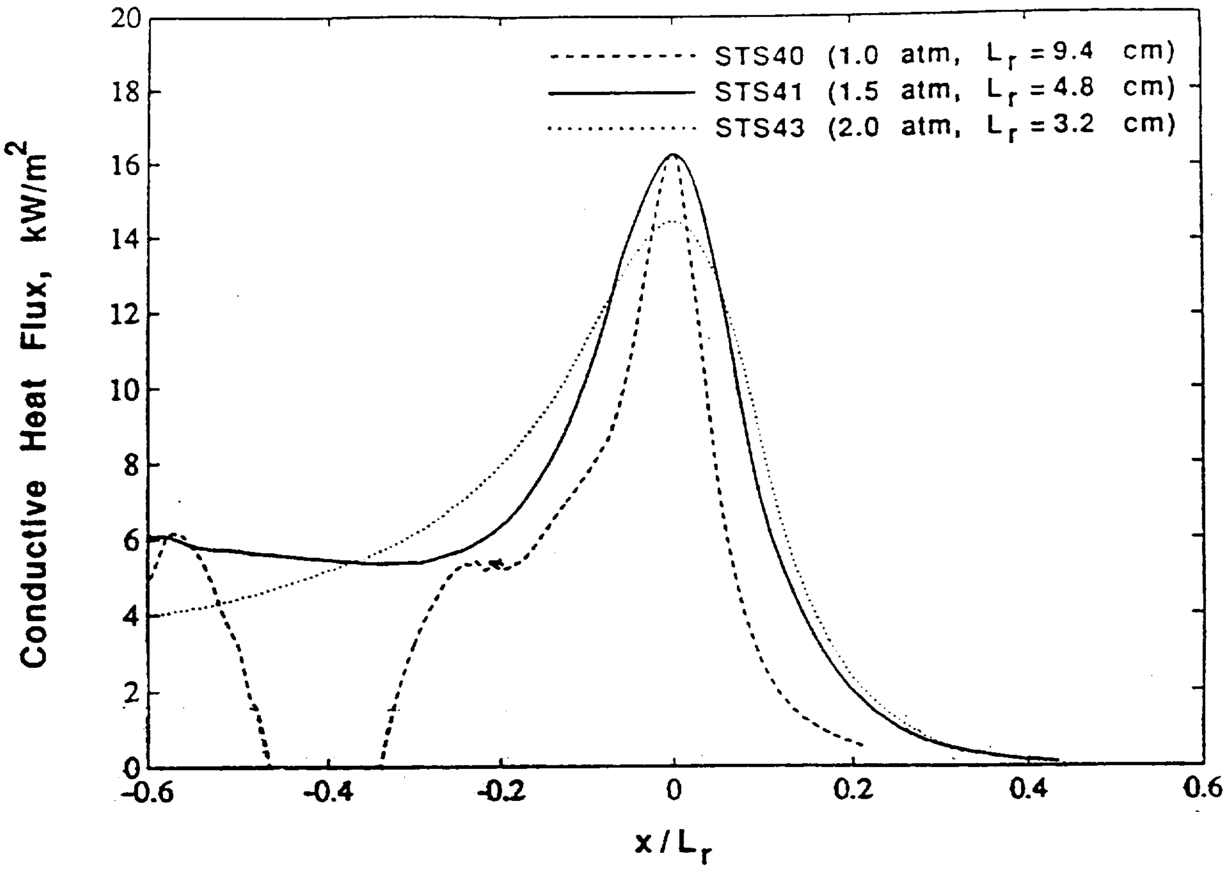
Fig. 2

R. Altenkirch, Mississippi State Univ.

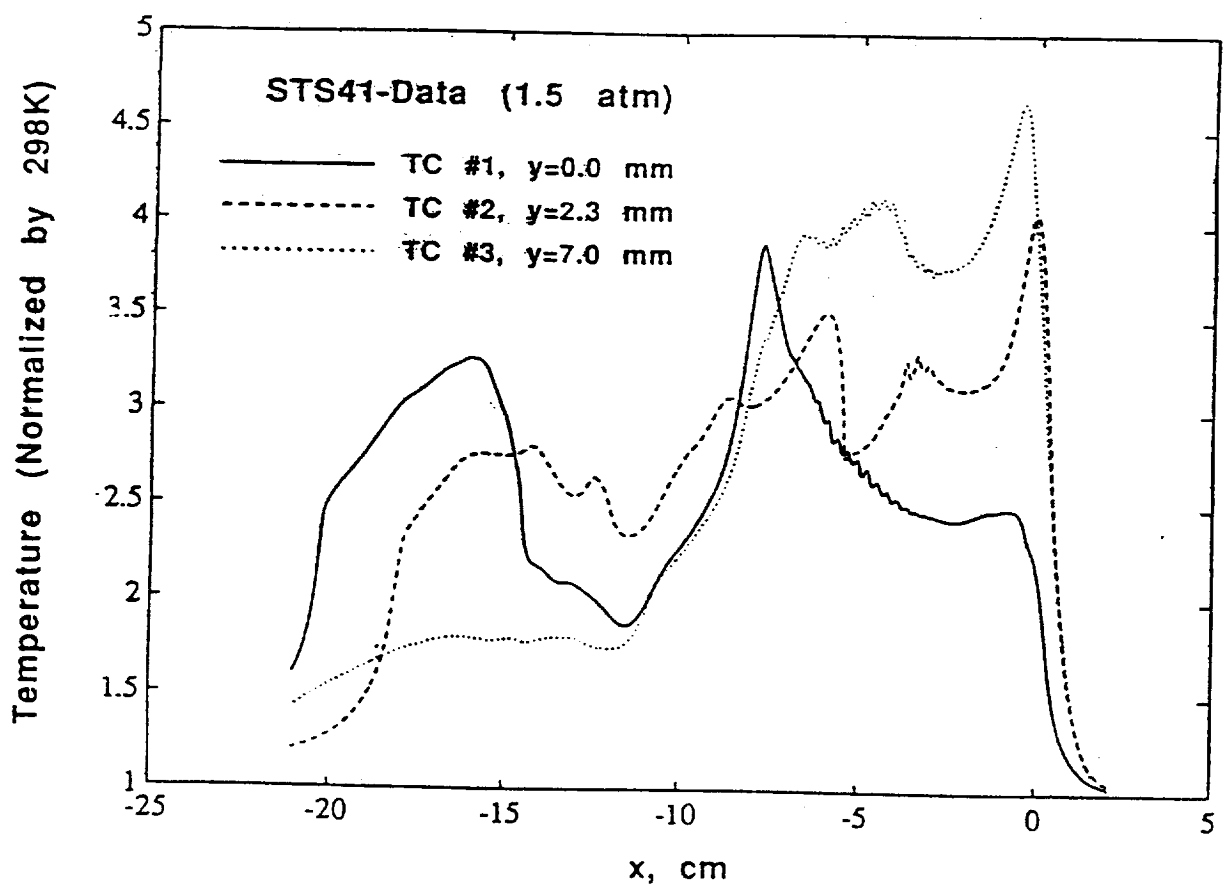

TC #1, y=0.0 mm
TC #2, y=2.3 mm
TC #3, y=7.0 mm
STS40-Data (1 atm)
Temperature (Normalized by 298K)
Time, s
0
10
20
30
40
50
60
70
1
1.5
2
2.5
3
3.5
4
4.5
5


STS43-Data (2 atm)
TC #1, y=0.0 mm
TC #2, y=2.3 mm
TC #3, y=7.0 mm
Temperature (Normalized by 298K)
Time, s


STS41-Data (1.5 atm)
TC #1, y=0.0 mm
TC #2, y=2.3 mm
TC #3, y=7.0 mm
Temperature (Normalized by 298K)
Time, s



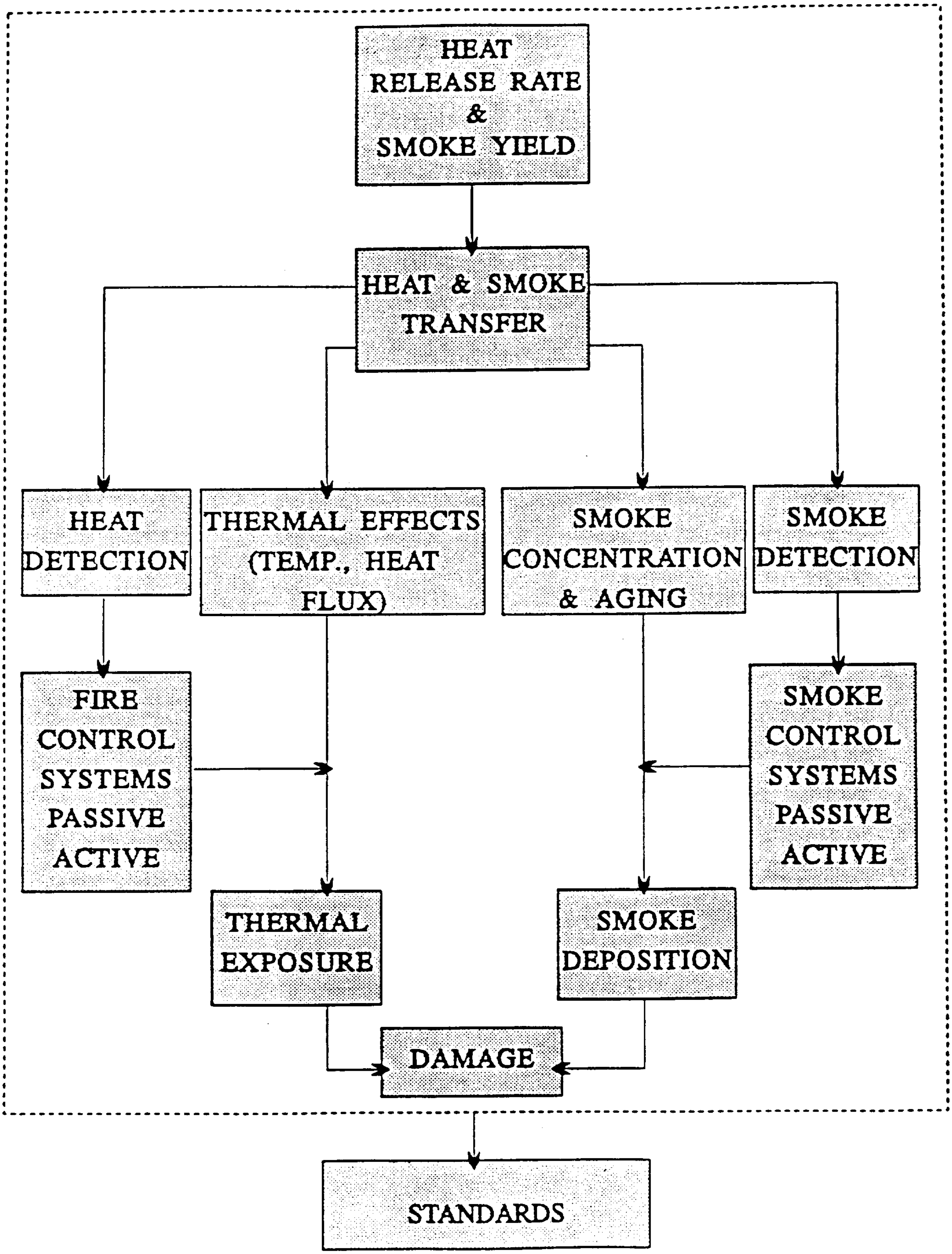
Conductive Heat Flux, kW/m2
x / Lr
STS40 (1.0 atm, Lr = 9.4 cm)
STS41 (1.5 atm, Lr = 4.8 cm)
STS43 (2.0 atm, Lr = 3.2 cm)



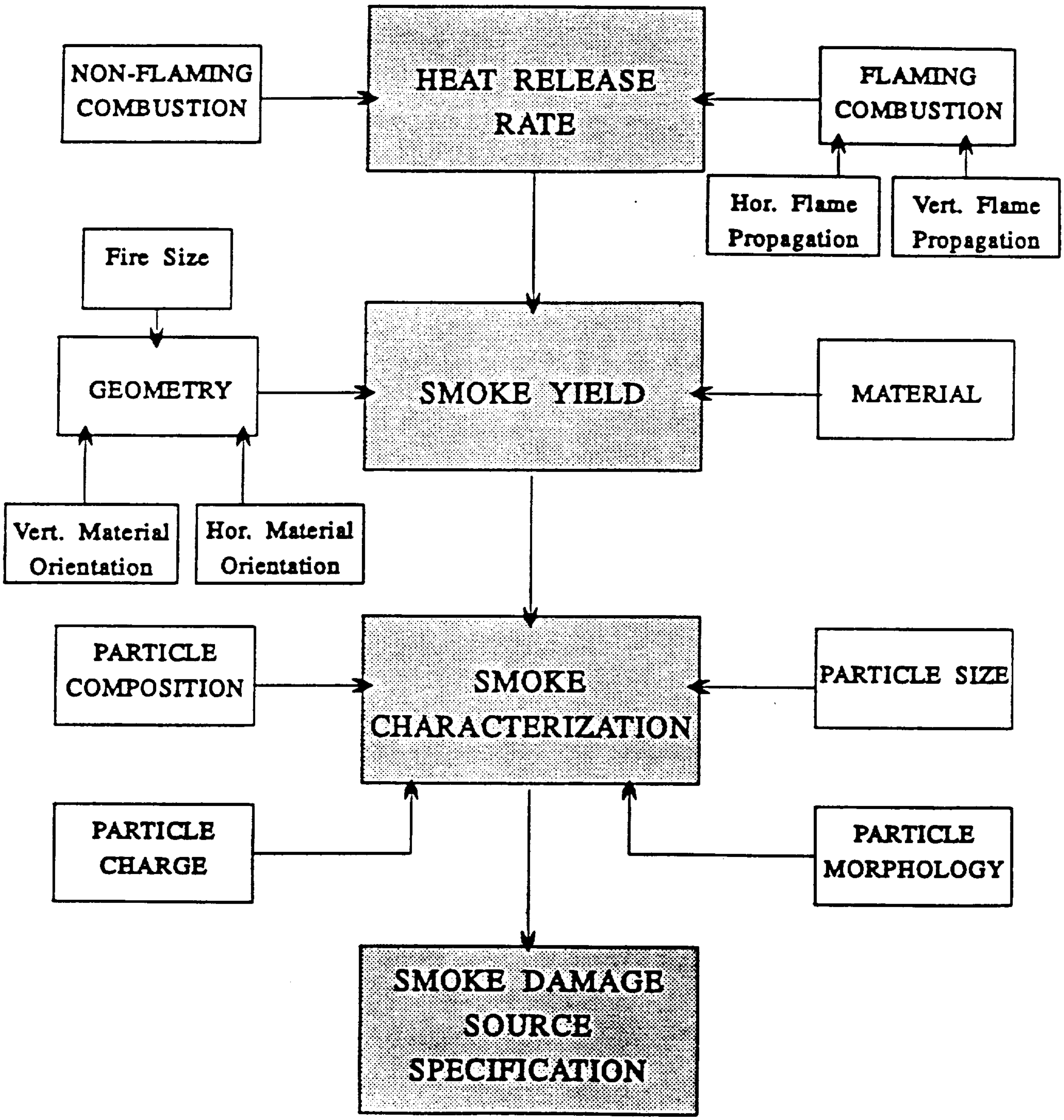
STS41-Data (1.5 atm)
TC #1, y=0.0 mm
TC #2, y=2.3 mm
TC #3, y=7.0 mm
Temperature (Normalized by 298K)
x, cm

Factory Mutual Research

METHODOLOGY FOR FIRE & SMOKE HAZARD ANALYSIS

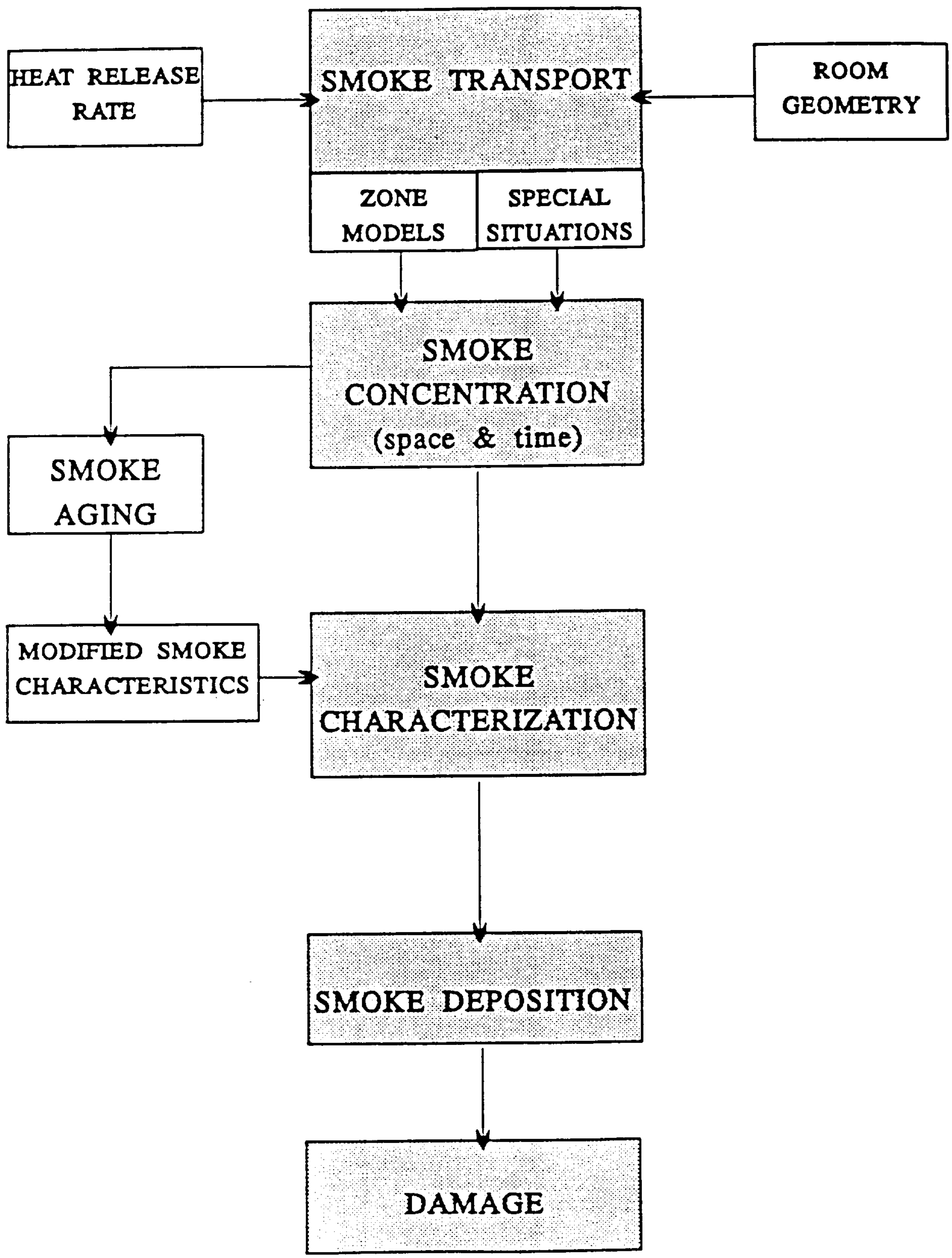


METHODOLOGY FOR FIRE & SMOKE HAZARD ANALYSIS



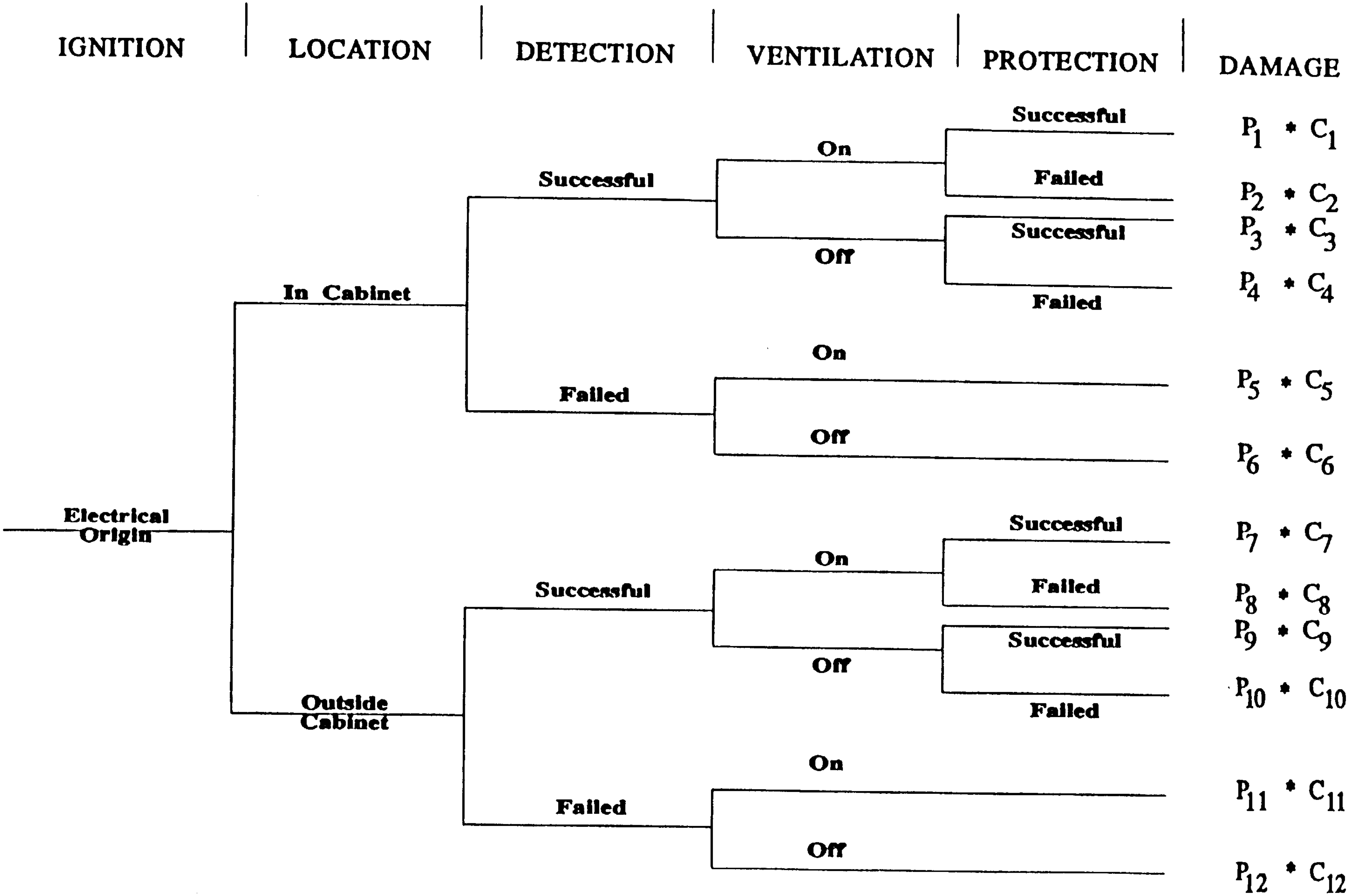
METHODOLOGY FOR FIRE & SMOKE HAZARD ANALYSIS

SMOKE TRANSPORT AND DEPOSITION

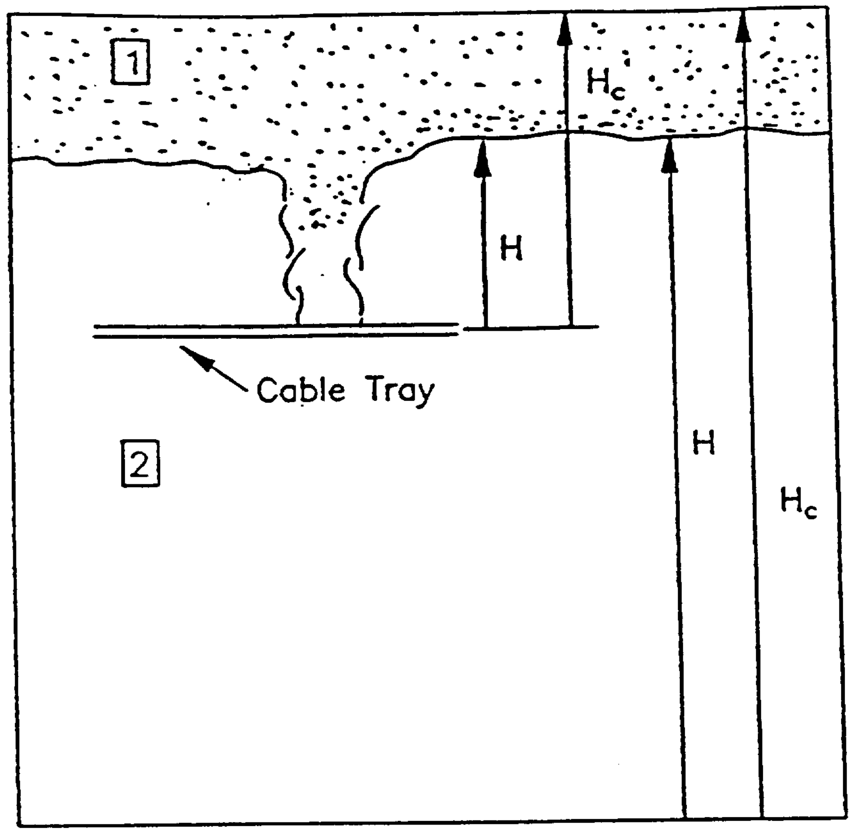


Factory Mutual Research

FIRE HAZARD ANALYSIS



TWO ZONE MODEL
HOT CEILING LAYER



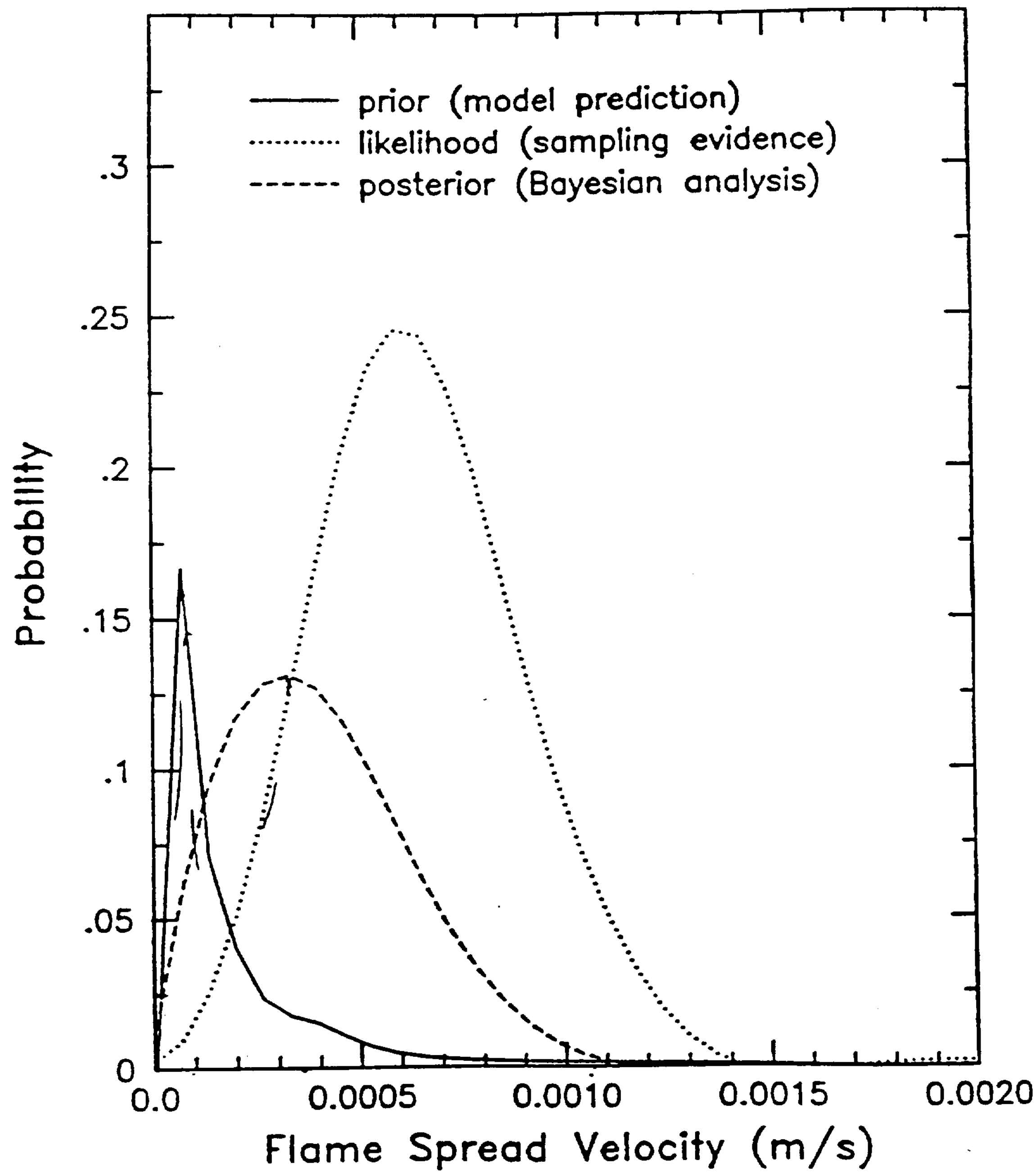
H	Distance of zone interface from room floor (m)
H'	Distance of zone interface from cable tray (m)
H_c	Room height (m)
H_c'	Distance from cable tray to room ceiling (m)

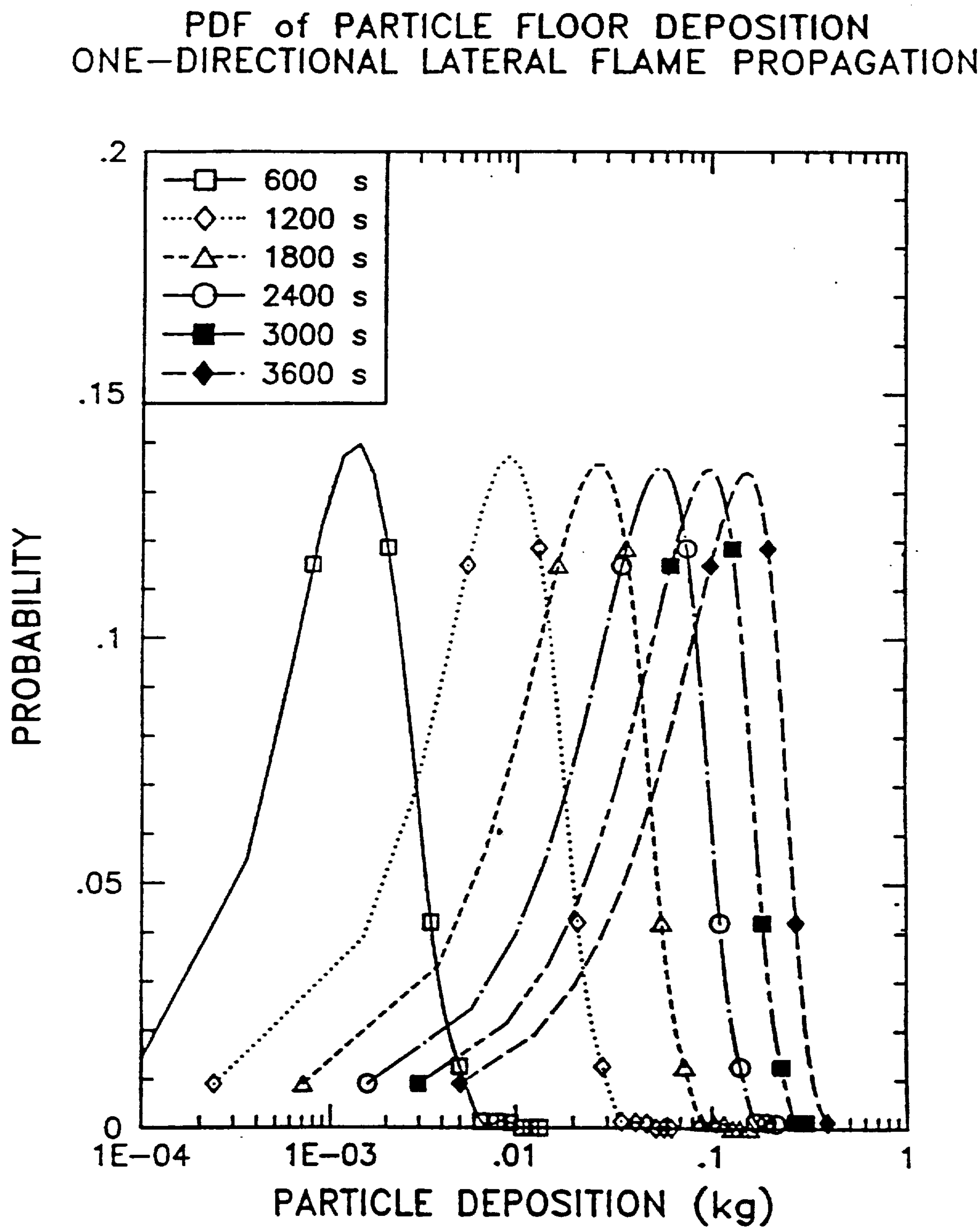
$$v=\frac{v_a(k\rho c)g(T_f-T_{ig})^2}{k\rho c(T_{ig}-T_s)^2}$$

$$\Phi=v_a(k\rho c)g(T_f-T_{ig})^2,\ \text{in kW}^2/\text{m}^3,$$

$$I=k\rho c(T_{ig}-T_s)^2$$

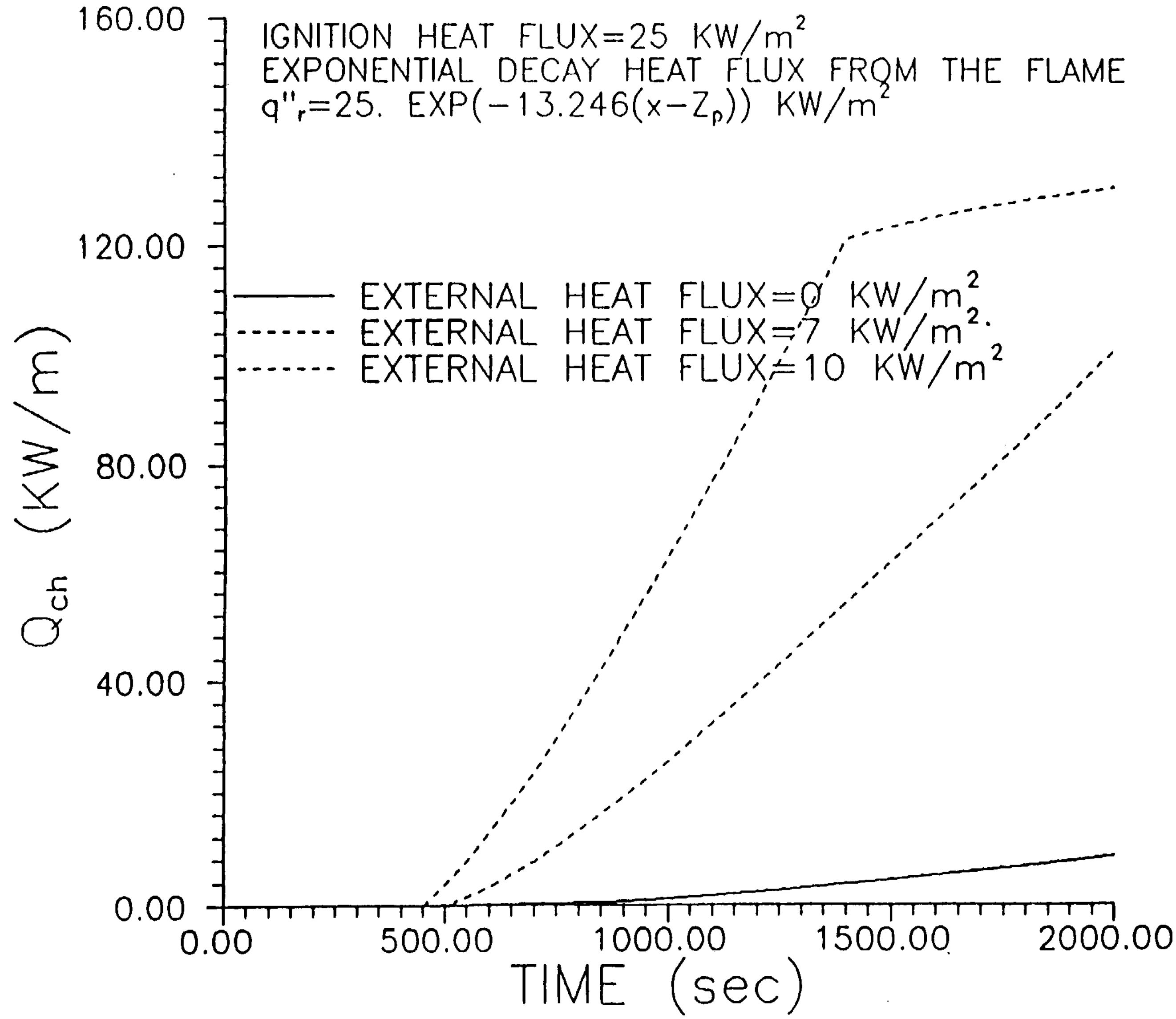
HORIZONTAL FLAME SPREAD VELOCITY ON CABLE TRAY
PROBABILITY DISTRIBUTION FUNCTIONS
Model Prediction Updated With Sampling Evidence



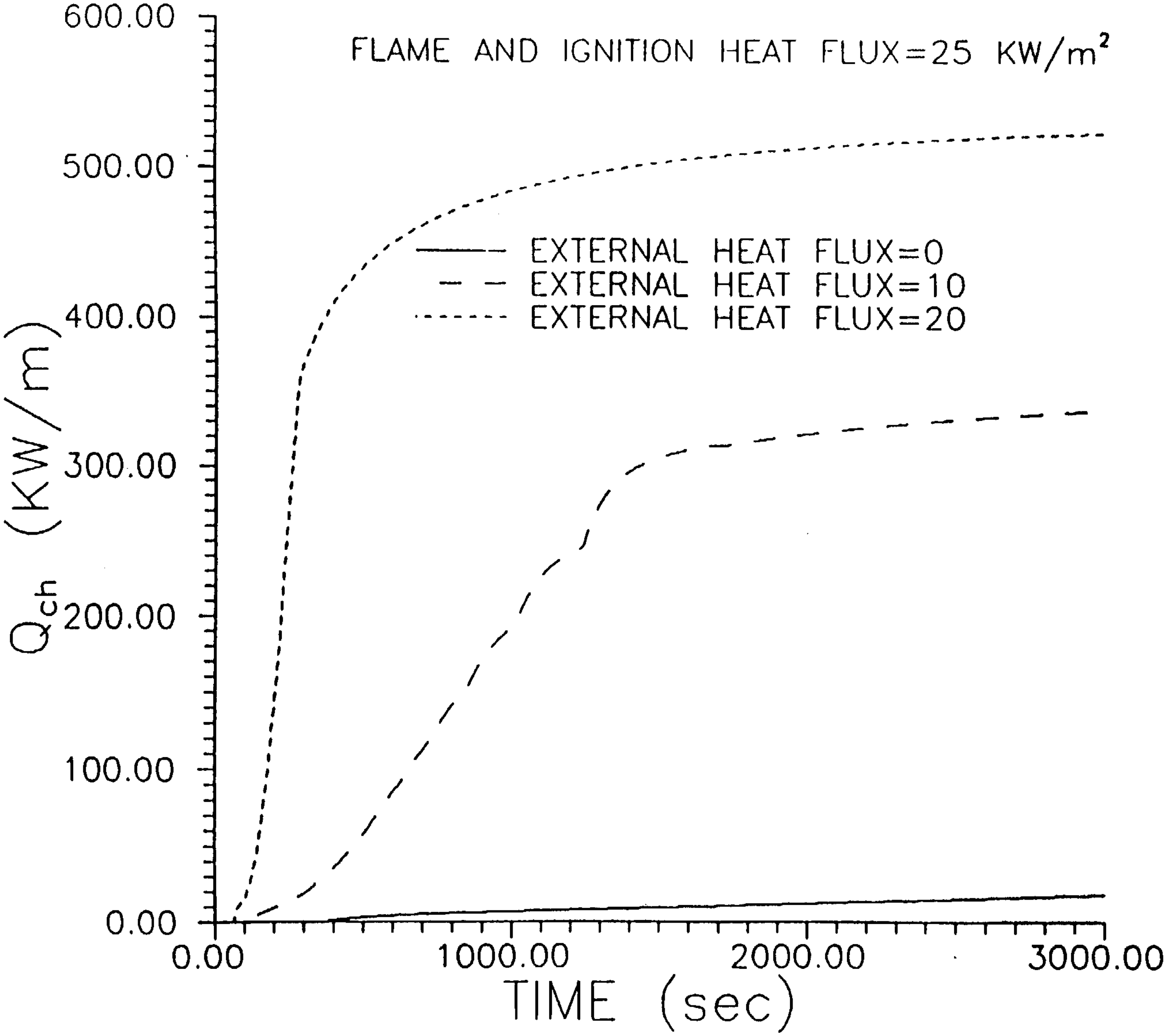


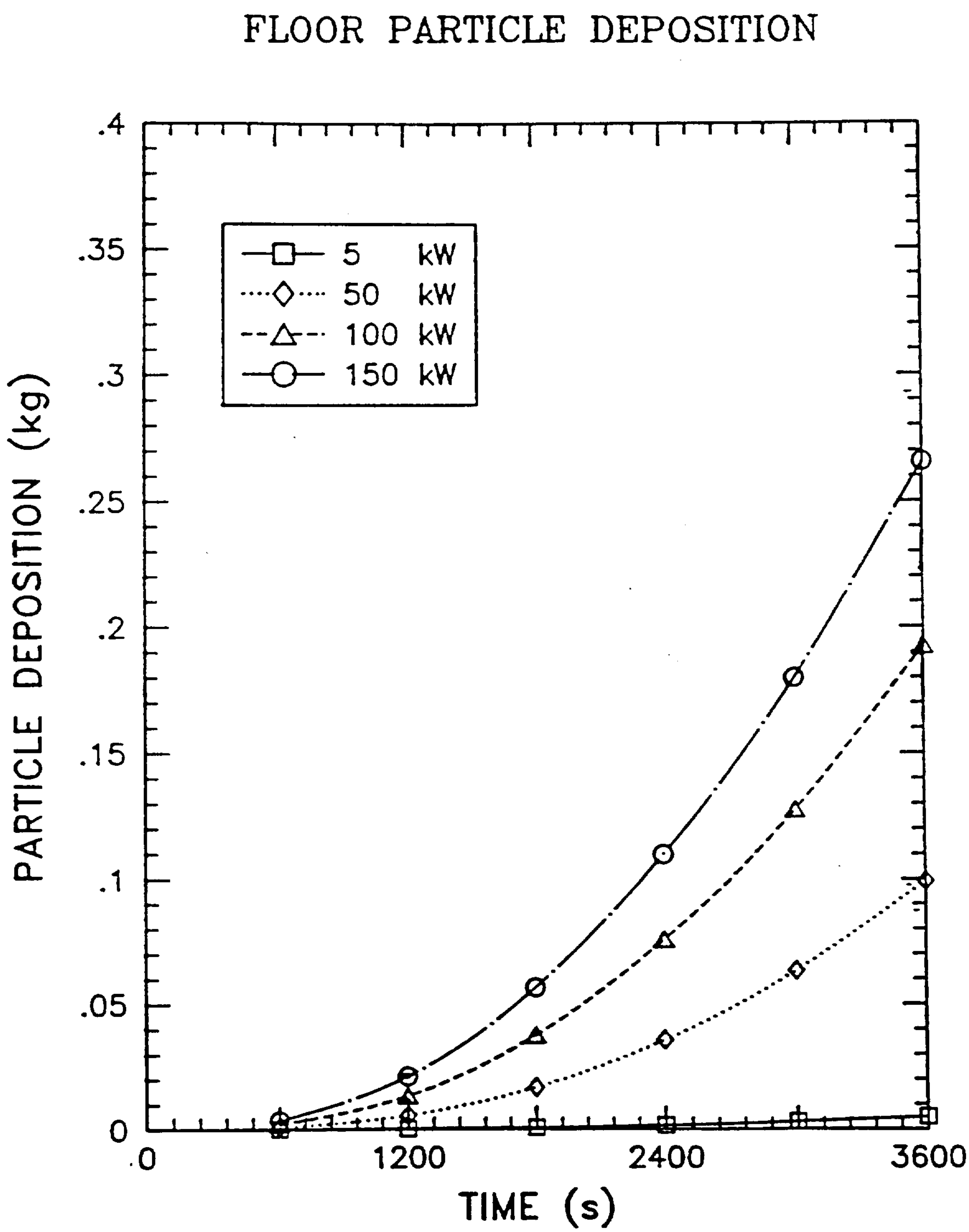
PDF of PARTICLE FLOOR DEPOSITION
ONE-DIRECTIONAL LATERAL FLAME PROPAGATION
600 s
1200 s
1800 s
2400 s
3000 s
3600 s
.2
.15
.1
.05
0
PROBABILITY
1E-04
1E-03
.01
.1
1
PARTICLE DEPOSITION (kg)

FIRE SPREAD AND GROWTH
Horizontal Cable Trays



FIRE SPREAD AND GROWTH
Vertical Cable Trays




FLOOR PARTICLE DEPOSITION
5 kW
50 kW
100 kW
150 kW
PARTICLE DEPOSITION (kg)
.4
.35
.3
.25
.2
.15
.1
.05
0
.0
1200
2400
3600
TIME (s)

Probability of Equipment Failure Exposed to Carbon Fibers

$$p = 1 - e^{-(E/E_m)}$$

with

E : exposure level in fiber-seconds

E_m: average exposure causing damage in fiber-seconds

GENERIC BUSINESS/INDUSTRY EQUIPMENT WITH MEAN EXPOSURE TO FAILURE VALUES (E_m IN FIBER SECONDS/METER^3)

Equipment	Failure Parameter E_m
Input power service equipment — transformers, breakers, switchgears	10^8
Power distribution buses and panels	10^8
Auxiliary power supply in parallel with power input	10^6
Standard-size computer used as a central facility controller	10^7
Keybord display unit	10^8
High-voltage power supply at a machine station	10^8
Interface unit used to buffer central computers to line controllers	10^8
Manual controller, associated with each electrically-operated machine	10^8
Mini-computer used as a programmable controller	10^8
Microprocessor used as a controller	10^8
High-voltage motor controller	10^8
Machine station servo-mechanism	10^8
Heater or oven control	10^8
Device to measure temperature, thickness, weight, position, motion, etc.	10^7

CONTAMINATION EXPOSURES AND EFFECTS

CONTAMINATION LEVEL ($\mu g/cm^2$)	AMBIENT CONDITIONS TYPICAL ENVIROMENT	EFFECTS METAL SURFACES	EFFECTS ELECTRONICS
ABOVE 77	VERY REACTIVE Rh>50% HOT PLASTICS FIRE SEAWATER SPRAY	FLASH RUST ETCHED SURFACES	HEAVY CORROSION CATASTROPHIC FAILURES
30	REACTIVE, Rh>60% MEDIUM TO HEAVY SMOKE	LIGHT RUST LONG TERM	ACTIVE CORROSION SHORT TERM
16	FACTORY ENVIROMENT Rh 30–90% – UNCONTROLLED	MARGINAL EFFECTS LONG TERM	MODERATE CORROSION LONG TERM
8	CONTROLLED ENVIROMENT Rh 45 – 55% T 65 – 75°F	NONE	SLIGHT SURFACE CORROSION LONG TERM
3	MIL STD SPEC HIGH RELIABILITY	NONE	NONE

Probability of Equipment Failure Exposed to Smoke Particles

$$p = 1 - e^{-\{(C-3)/C_o\}}$$

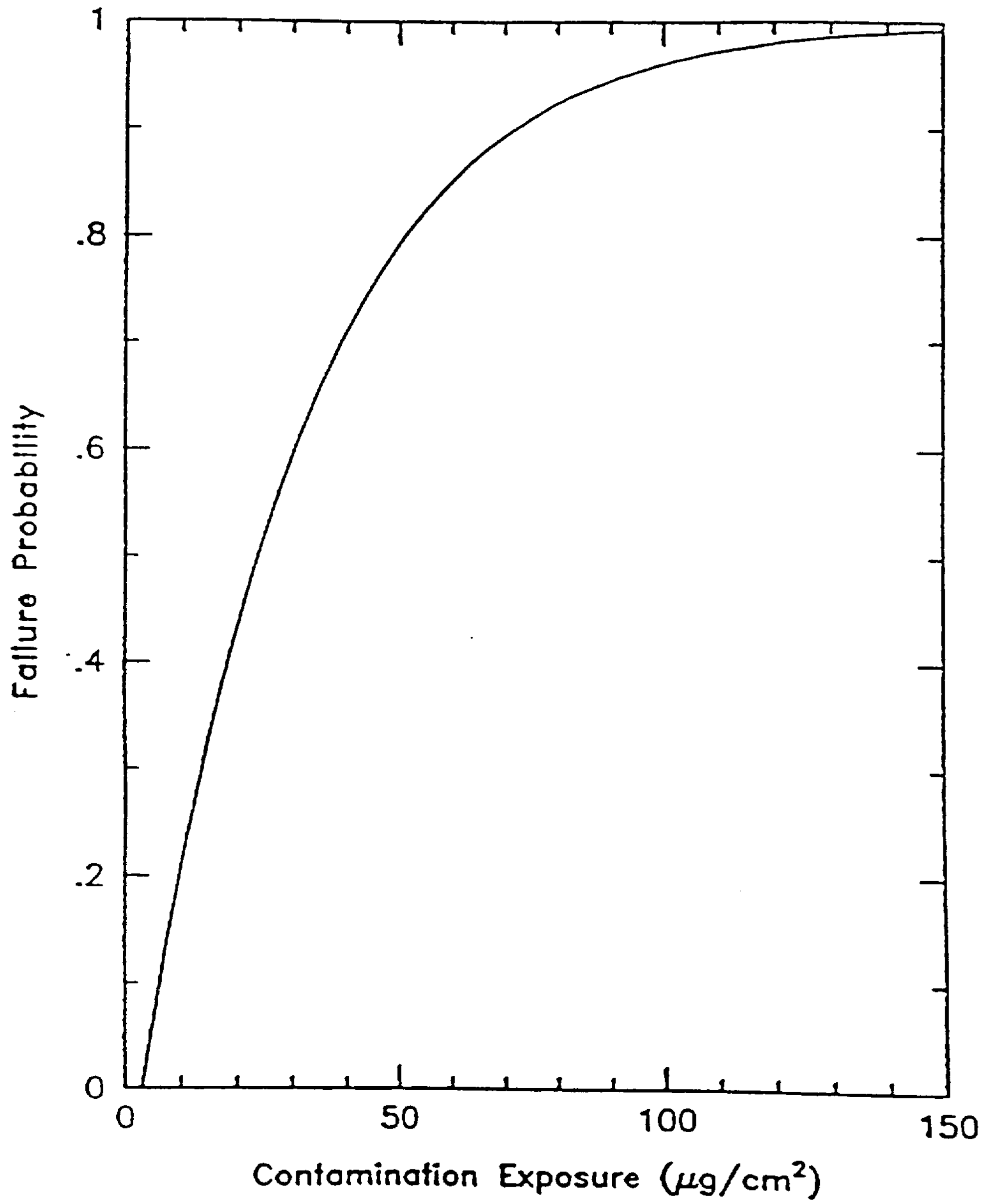
with

C : surface concentration of smoke particles in $\mu g/cm^2$

Co: average surface concentration of smoke particles causing damage, in $\mu g/cm^2$

DEVICE FAILURE PROBABILITY

AFTER SMOKE EXPOSURE



APPLICATION EXAMPLE: SMOKE DAMAGE PROBABILITY FOR

FIRE OF 100 kW

TIME INTERVAL (seconds)	SOOT SURFACE DEPOSITION (μg)	SOOT CONCENTRATION (μg/cm²) (onedirectn)	DAMAGE PROBABILITY (onedirectn)	SOOT CONCENTRATION (μg/cm²) (bidirectn)	DAMAGE PROBABILITY (bidirectn)
600	$2 \cdot 10^6$	0.11	0	0.22	0
1200	$(1.5) \cdot 10^7$	0.85	0	1.7	0
1800	$4 \cdot 10^7$	2.27	0	4.54	0.044
2400	$8 \cdot 10^7$	4.5	0.042	9	0.158
3000	$(1.5) \cdot 10^8$	8.5	0.146	17	0.326
3600	$(2.5) \cdot 10^8$	14.17	0.272	28.34	0.496

FIRE HAZARD CONTROL AND RISK MINIMIZATION ON SPACE PROGRAMS

Workshop on Spacecraft Fire Safety
UCLA - 31 October - 1 November 1991

John Pauperas, Safety
Howard Kimzey, Consultant to M&P
Andrea Gardner, FCS

McDonnell Douglas Space Systems Company
Huntington Beach, CA; Houston, TX

Note: The material in this presentation does not necessarily reflect DOD or NASA Fire Safety Policy for Manned Space Flight or implementation of design requirements for Space Station

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FIRE HAZARD CONTROL AND RISK MINIMIZATION ON SPACE PROGRAMS

Outline

- Fire Hazard and System Safety - Pauperas
- Design of Spacecraft, including Material Selection, and it's Role in Accidental Fire -Kimzey
- Fire Detection and Suppression on Manned Spacecraft -Gardner

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J. Pauperas & A. Gardner McDonnell Douglas Space Systems

UNDESIRED EVENT ON MANNED SPACECRAFT

- "Probably no greater fear exists in manned spaceflight than onboard fire. In space there are no fire exits."
- "In preliminary design is a droplet burning experiment that will ignite single droplets of various fuels. The large spherical droplets will simulate the microscopic ones found in engines. A particle cloud combustion experiment will ignite a mist in a flame tube. Ignition at one end will allow flame propagation through the tube to be studied. Weightlessness assures a uniform mixture and eliminates settling."

From an article in Aerospace America, May 1986, "Safety in the Space Station" by R. DeMeis.

SAFETY DESIGN PRECEDENCE

3.1.9 SAFETY

The flight elements and systems and ground systems shall meet the safety design requirements herein.

3.1.9.1 ORDER OF DESIGN PRECEDENCE

Hardware and software design shall reflect the following order of precedence:

(1) Elimination of hazards by removal of hazardous sources and operations by appropriate design measures;

(2) Prevention of hazards through the use of safety devices or features;

(3) Control of hazards through the use of warning devices, special procedures, and/or emergency devices; and

(4) Minimization of hazards through a maintainability program and adherence to an adequate maintenance and repair schedule(s).

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MIL-STD-882 B HAZARD SEVERITY DESCRIPTIONS

4.5.1 HAZARD SEVERITY: HAZARD SEVERITY CATEGORIES ARE DEFINED TO PROVIDE A QUALITATIVE MEASURE OF THE WORST CREDIBLE MISHAP RESULTING FROM PERSONNEL ERROR; ENVIRONMENTAL CONDITIONS; DESIGN INADEQUACIES; PROCEDURAL DEFICIENCIES; OR SYSTEM, SUBSYSTEM, OR COMPONENT FAILURE OR MALFUNCTION AS FOLLOWS:

Description	Category	Mishap Definition
CATASTROPHIC	I	Death or system loss.
CRITICAL	II	Severe injury, severe occupational illness, or major system damage.
MARGINAL	III	Minor injury, minor occupational illness, or minor system damage.
NEGLIGIBLE	IV	Less than minor injury, occupational illness, or system damage.

MIL-STD-882 B HAZARD PROBABILITY DESCRIPTIONS

4.5.2 HAZARD PROBABILITY: THE PROBABILITY THAT A HAZARD WILL BE CREATED DURING THE PLANNED LIFE EXPECTANCY OF THE SYSTEM CAN BE DESCRIBED IN POTENTIAL OCCURRENCES PER UNIT OF TIME, EVENTS, POPULATION, ITEMS, OR ACTIVITY. AN EXAMPLE OF A QUALITATIVE HAZARD PROBABILITY RANKING IS:

Description *	Level	Specific Individual Item	Fleet or Inventory **
FREQUENT	A	Likely to occur frequently.	Continuously experienced.
PROBABLE	B	Will occur several times in life of an item.	Will occur frequently.
OCCASIONAL	C	Likely to occur sometime in life of an item.	Will occur several times.
REMOTE	D	Unlikely but possible to occur in life of an item.	Unlikely but can reasonably be expected to occur.
IMPROBABLE	E	So unlikely, it can be assumed occurrence may not be experienced.	Unlikely to occur, but possible.

* Definitions of descriptive words may have to be modified based on quantity involved.
** The size of the fleet or inventory should be defined.

MIL-STD-882B EXAMPLE OF HAZARD RISK ASSESSMENT MATRIX

FREQUENCY OF OCCURRENCE	HAZARD CATEGORIES I CATASTROPHIC	II CRITICAL	III MARGINAL	IV NEGLIGIBLE
A -- FREQUENT	1A	2A	3A	4A
B -- PROBABLE	1B	2B	3B	4B
C -- OCCASIONAL	1C	2C	3C	4C
D -- REMOTE	1D	2D	3D	4D
E -- IMPROBABLE	1E	2E	3E	4E

Hazard Risk Index	Suggested Criteria
1A, 1B, 1C, 2A, 2B, 3A	Unacceptable
1D, 2C, 2D, 3B, 3C	Undesirable (MA decision required)
1E, 2E, 3D, 3E, 4A, 4B	Acceptable with review by MA
4C, 4D, 4E	Acceptable without review

LIFE CYCLE AND HISTORICAL PERSPECTIVE

- Fire Safety on Space Programs
  - Manufacturing Facility and Transport (Example - OPTIONAL)
  - ETR and WTR (Range Safety and Facility Protection)
    - Solid propellant
    - Liquid propellant
    - Ordnance/Explosives
  - Launch Vehicle and Payload
    - Expendable
    - Reusable
    - Retrievable
  - Spacecraft
    - Unmanned
    - Man-tended
    - Permanently manned

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LIFE CYCLE AND HISTORICAL PERSPECTIVE

- Major MDSSC Manned Spacecraft/Launch Vehicle Programs at the Huntington Beach, CA, Facility (since 1964)
  - MOL (Cancelled 1969)
  - Saturn Launch Vehicle IVB Stages (Mid 1960's)
  - Orbital Workshop/Skylab (1973)
  - Delta Launch Vehicles
  - Payload Assist Modules for Launch from Shuttle
  - Space Station WP-2
    - Resource nodes
    - Airlock with hyperbaric chamber

COMMON CHARACTERISTICS FOR FIRE SAFETY IN MANNED SPACECRAFT

- Isolation/Exclusion of Elements of Combustion
- Materials Selection and Control
- Elimination/Control of Ignition Sources
- Atmospheric Composition, Pressure and Ventilation Control
- Containment, Fire Barriers and Damage Control
- Modular Habitation, Isolation Hatches, and Egress Provisions
- Distributed and Failure Tolerant Systems Essential for Survival
- Emergency Crew Survival Provisions and/or Assured Return
- Fire Detection and Suppression

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TYPICAL IGNITION SOURCES THAT MUST BE ELIMINATED/CONTROLLED

- **Electrical**
  - Spark discharge/arcing, electrostatic discharge, short circuit/resistance heating, electromagnetic radiation etc. from electrical equipment
- **Open Flame**
  - Matches or lighters, pilot lights, heating equipment, welding or cutting torches
- **Frictional Heating**
  - Slipping drive belts or pulleys, poorly lubricated machinery, overheated equipment (bearings), grinding or machining, fan impellers rubbing on casing
- **Sparks**
  - Engine exhausts, electrical systems, tools dropped on hard surfaces, grinding or machining, cigarettes, shoe nails striking other metal, dragging metallic containers, *meteoroid/orbital debris penetration*
- **Electrostatic Discharge**
  - Ungrounded equipment, slipping drive belts and pulleys, flow of non-polar fluids through pipes into containers
- **Autoignition**
  - Selfignition of flammable gas or vapor air mixture in normal environment
- **Autooxidation**
  - Propellants during storage due to deterioration, confined and inadequately vented accumulations of paper, cloth, etc. when contaminated with oil, paint, grease,etc.
- **Catalytic Ignition**
  - Catalytic materials, such as metal oxides, can promote oxidation on their surfaces leading to high local temperature and subsequent ignition of the entire mixture

Check list abstracted from CPIA #394, September 1984

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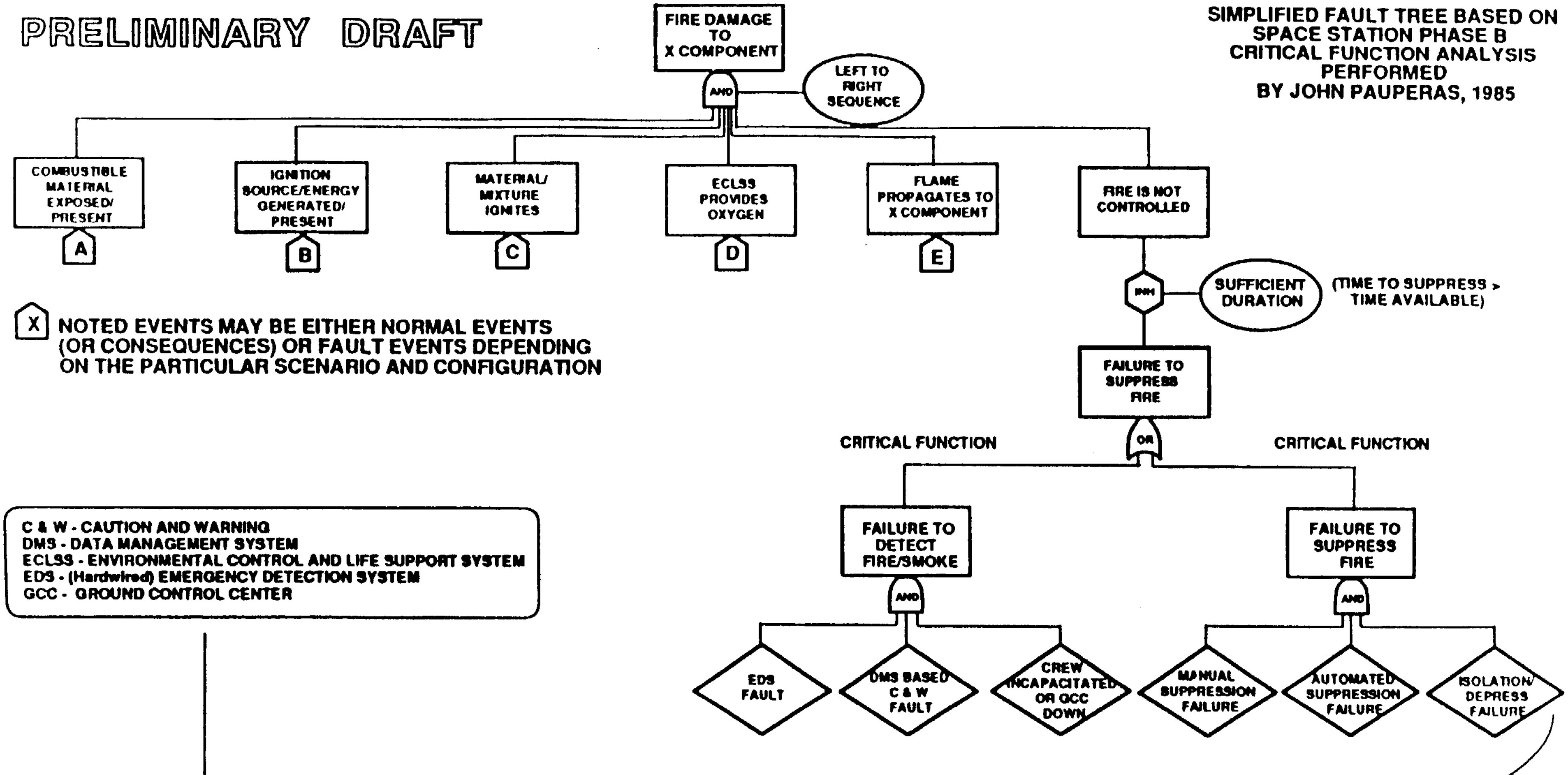
PRELIMINARY DRAFT

SIMPLIFIED FAULT TREE BASED ON
SPACE STATION PHASE B
CRITICAL FUNCTION ANALYSIS
PERFORMED
BY JOHN PAUPERAS, 1985



X NOTED EVENTS MAY BE EITHER NORMAL EVENTS (OR CONSEQUENCES) OR FAULT EVENTS DEPENDING ON THE PARTICULAR SCENARIO AND CONFIGURATION

C & W - CAUTION AND WARNING
DMS - DATA MANAGEMENT SYSTEM
ECLSS - ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM
EDS - (Hardwired) EMERGENCY DETECTION SYSTEM
GCC - GROUND CONTROL CENTER

STAGES OF FIRE/ HAZARD LEVEL	INCIPIENT	SMOLDERING	FLAME	HEAT
DURATION	HOURS TO SECONDS	MINUTES TO SECONDS	SECONDS	
CONTROLS	MATERIALS AND PROCESS CONTROL, CONTROL OF IGNITION SOURCES, AND ADMINISTATIVE CONTROLS	DETECTION, ANNUNCIATION, ISOLATION AND SUPPRESSION		

DESIGN OF SPACECRAFT, INCLUDING MATERIAL SELECTION, AND IT'S ROLE IN ACCIDENTAL FIRE

- Introduction - Ground vs Space
- Design Requirements for Manned Spacecraft
- Procedure for Hardware Certification
- Designer's Role
- Customer's Role

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GROUND vs SPACE

- On the Ground we typically can:

1. Assess the situation - deciding whether we can deal with it using available resources, or
2. Evacuate the area and call for help from the professionals who will soon arrive equipped and fully trained.

- In Space, Specifically, he or she will:

1. Assess the situation and
2. Take appropriate action utilizing what is provided on the scene.

With advance planning this may be:

a. Verify there is an actual emergency.
b. If a fire, turn off power in affected area, but leaving area lights on.
c. Turn off air flow.
d. Assist any injured crewmen.
e. Isolate by evacuation and, if appropriate, close hatches.
f. Release extinguishing agent or vent the compartment.

DESIGN REQUIREMENTS FOR MANNED SPACECRAFT

NASA NHB 8060.1B (.. OR C) - Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials.

NASA HDBK-527/JSC-09604 - Materials Selection List.

NASA MSFC-SPEC-522B - Control of Stress Corrosion Cracking.

NASA JSC 20584 - Toxicity, Acceptable Concentrations (24 hour Exposure).

NASA SP-R-0022A - Vacuum Stability Requirements for Polymers.

NASA-STD-3000 - Human Factors.

NASA SP-8063 - Lubrication, Friction, and Wear.

Others - Specific for the Program, such as Apollo, Gemini, Apollo-Soyuz, Skylab, and Space Station.

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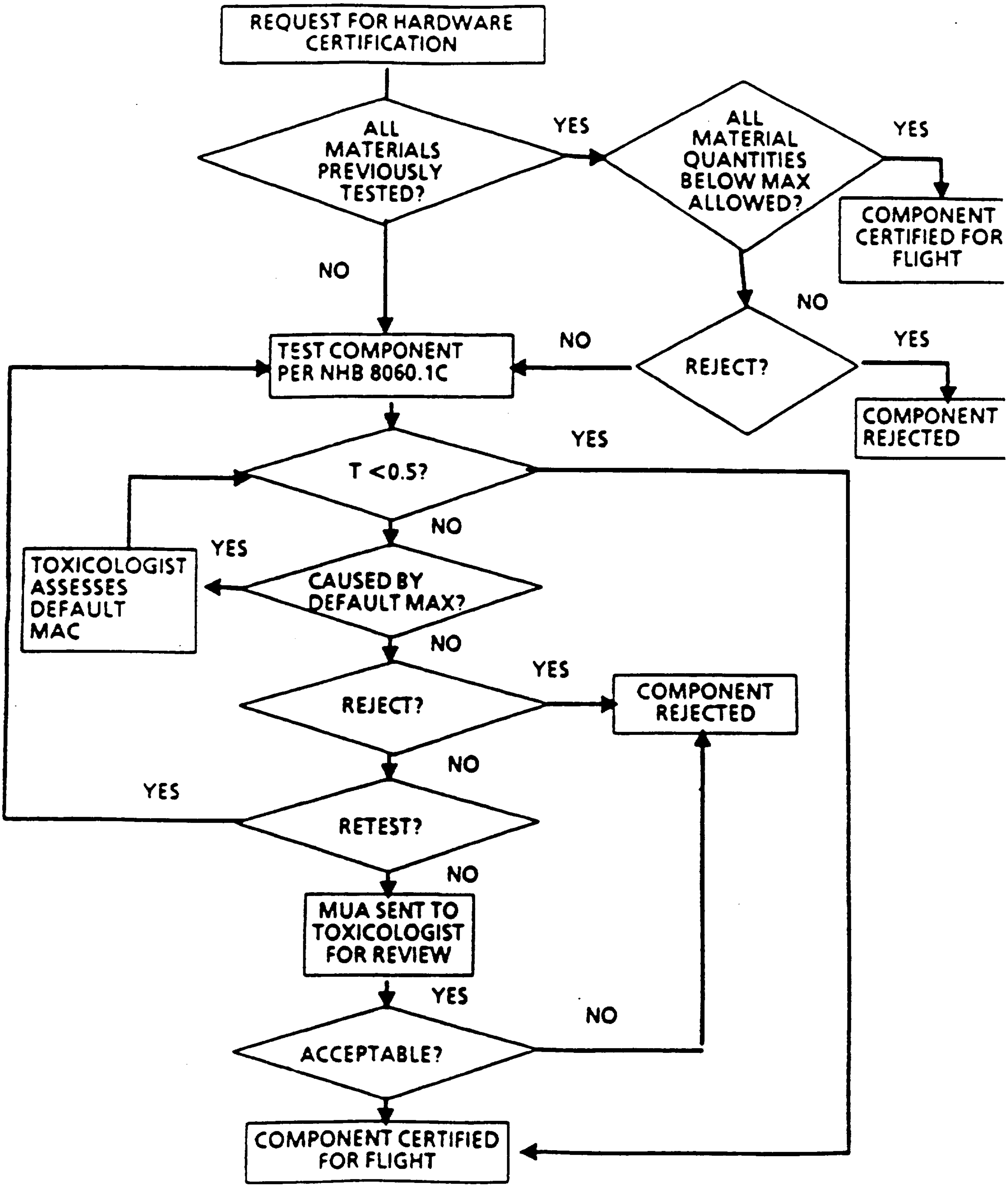
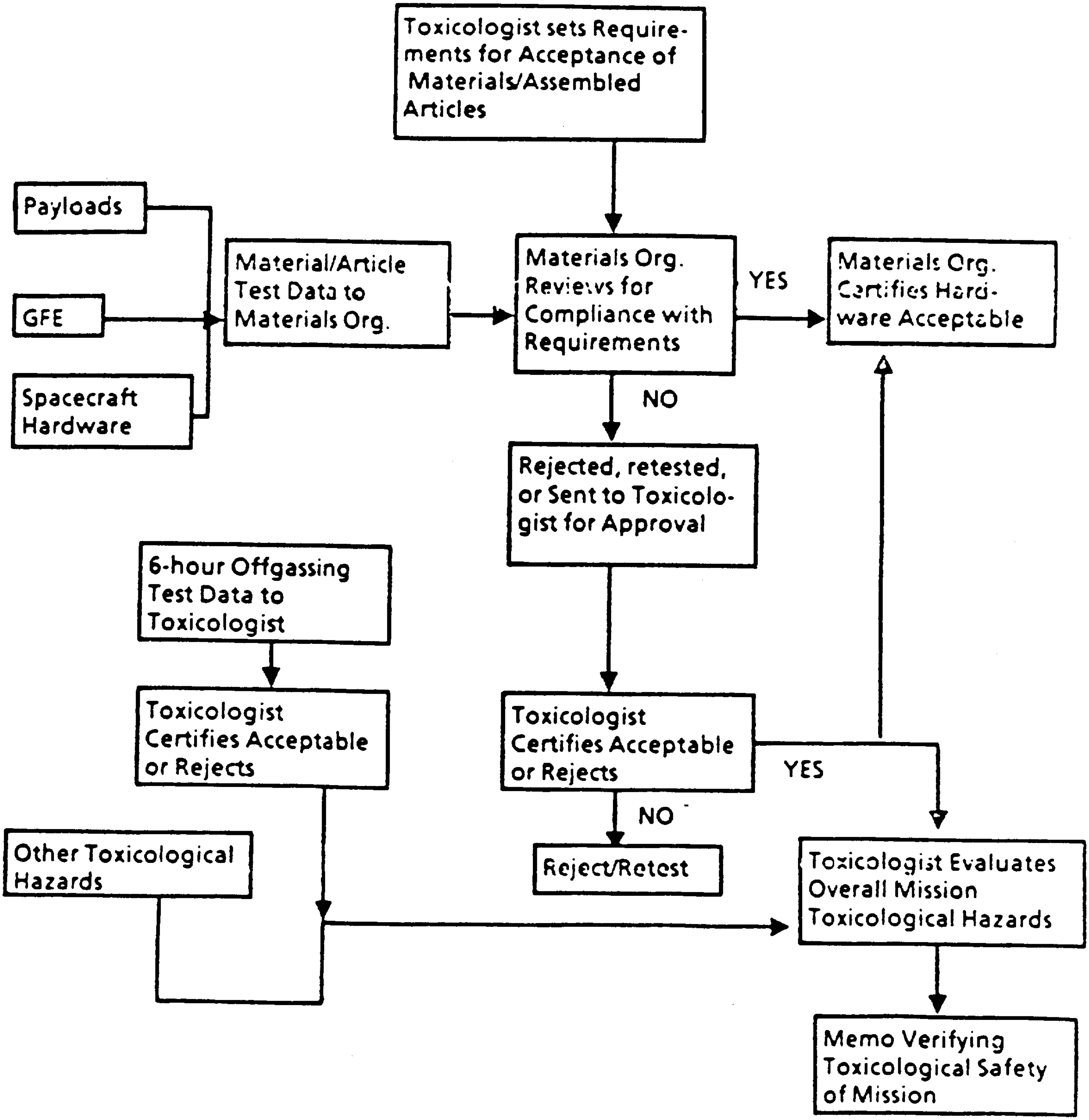
PROCEDURE FOR HARDWARE CERTIFICATION



PROCEDURE FOR TOXICITY ASSESSMENT



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FIRE DETECTION AND SUPPRESSION (FDS) ON MANNED SPACECRAFT

- Design Requirements for FDS
- Fire Detection in Crew Volumes
- Fire Suppression in Crew Volumes
- Typical Overview Diagram of FDS
- Candidate Suppressants
- Closed-out Volume Considerations

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DESIGN REQUIREMENTS FOR FDS

- Sound alarm sufficiently early to assure opportunity for safe crew egress
- Isolate fire
- Provide capability to extinguish any fire or surface combustion
- Restore suppression capability after discharge
- Use nontoxic extinguishing agents that minimize toxic by-products
- Provide capability for remote activation

FIRE DETECTION IN CREW VOLUMES

- Visual or odor detection by crew
- Smoke sensors
  - Require adequate cabin ventilation to move air-borne smoke to sensors
  - Effectiveness determined by obscuration level, usually on the order of 0.5%/ft or 1.5E9 particles/cu ft
- Flame sensors
  - Viewing angle of the optical sensors determines position to maximize volume sensed
  - Problems with false detection of other light sources
- Thermal sensors

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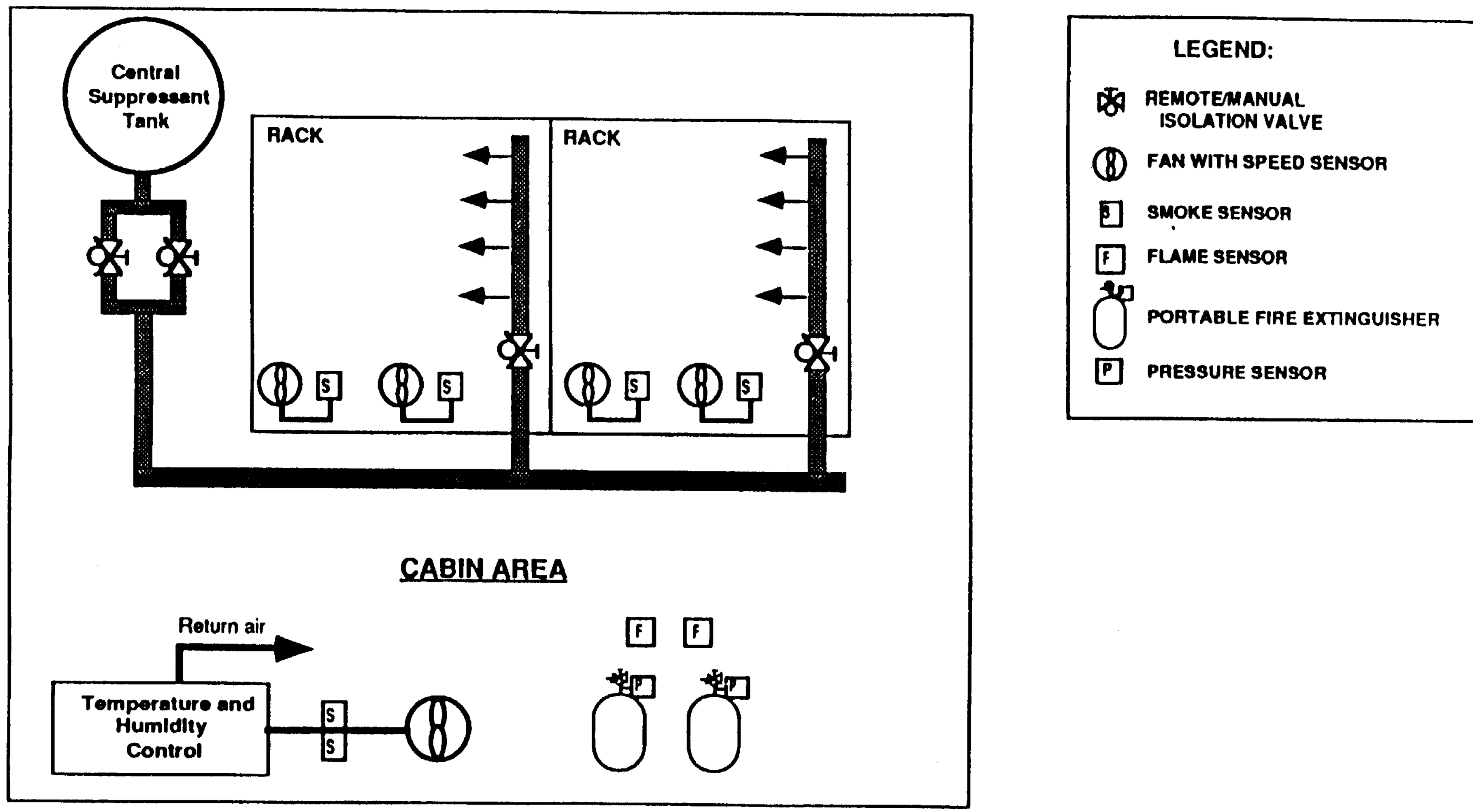
FIRE SUPPRESSION IN CREW VOLUMES

- Isolate module where fire is detected
- Turn off power to affected areas, while maintaining power to:
  - lights
  - validation sensors
  - suppressant release valves
  - other critical equipment
- Vent to vacuum to suppress fire when craft unoccupied
- Portable extinguishers used for suppression when crew present
  - Air revitalization, trace contaminant control subsystems scrub air following fire

TYPICAL OVERVIEW DIAGRAM OF FDS



CANDIDATE SUPPRESSANTS

- Nitrogen and carbon dioxide currently the primary suppressants

- Nitrogen
  - Adequate suppression capabilities
  - Extremely poor performance in portable extinguishers
  - Non-toxic to crew

- Carbon dioxide
  - Good suppression capabilities
  - Adequate performance in portable extinguishers
  - Potential crew physiological problems

CLOSED-OUT VOLUME CONSIDERATIONS

- Smoke sensors preferable
  - Inadequate light for flame sensors
- Air circulation over sensors
  - Air-cooled volumes use same fan
  - Cold-plated volumes require addition of fan
  - Volumes without electrical equipment do not need sensing
- Piccolo tubes can improve detection by drawing air directly from electrical equipment
- Suppressant released and contained within volume
  - Through piccolo tubes or with portable extinguisher
  - Suppressant concentration must be maintained for some minimum amount of time
- Suppressant and toxins vent slowly to cabin where they are scrubbed in air revitalization subsystem

MDSSC

The Design of Spacecraft, including Material Selection, And its Role in Accidental Fire

Generally speaking, the interior of a manned spacecraft is designed with approximately the same kinds of equipment as might be found in a home or workplace. This infers that accidental fires are possible since the atmosphere will typically be ambient air containing 20 percent oxygen, and the materials are, in some cases, flammable. The lessons learned since the 1960's when Mercury, Gemini, and Apollo were flown with pure oxygen, and specifications were still being written, has provided us today with much test data regarding the flammability of materials and other design details, so that the possibility of an accidental fire has been minimized. We have recognized the need for fire detectors and extinguishing capability, and crews are trained according to the flight objectives. But abundant energy, which might be released in the event of a series of failures and cause a fire, is available. Thus we have reduced the risk considerably. Yet we might compare a residence or work-place as to what are the possible courses of action for the occupant. The main differences, of course, are the consequences of a fire.

GROUND vs SPACE

On the ground we typically can:

1. Assess the situation - deciding whether we can deal with it using available resources, or
2. Evacuate the area and call for help from the professionals who will soon arrive equipped and fully trained.

In space, specifically, he or she will:

1. Assess the situation and
2. Take appropriate action utilizing what is provided on the scene. With advance planning this may be:
   a. Verify there is an actual emergency.
   b. If a fire, turn off power in affected area, but leaving area lights on.
   c. Turn off air flow.
   d. Assist any injured crewmen.
   e. Isolate by evacuation and, if appropriate, close hatches.
   f. Release extinguishing agent or vent the compartment.

H. Kimzey, McDonnell Douglas

DESIGNER'S ROLE

The designer's role in minimizing a fire includes:

1. Careful selection of materials that are self-extinguishing for the habitable environment. [NASA NHB 8060.1B]
2. Consider alloys with adequate stress corrosion properties for a given application. [NASA MSFC-SPEC-522B]
3. Provide a layout to preclude propagation of failures as from one flammable material to another, or from a payload to the vehicle.
4. Select pressure vessels that will not rupture under combined loads (mechanical, thermal, etc.) or that will fail in a non-catastrophic manner.
5. Provide adequate factors of safety for lines and fittings.
6. Allow for decompression or recompression consistent with the flight profile.
7. Provide for hazardous materials:
   a. Fluid compatibility.
   b. No single point failures, including heaters failing "ON".
   c. Batch lot control.
8. Avoidance of possible toxic consequences from offgassing in manned areas. [JSC 20584]
9. Avoidance of outgassing of exterior materials [NASA SP-R-0022A: 1% TWL, 0.1% VCM] which can produce a loss of critical materials causing plating or sublimation of unwanted coatings, adversely influencing:
   a. Thermal coatings
   b. Dielectric property of surfaces
   c. Optical Surfaces
   d. Solar Panels
10. Avoid incompatibilities with atomic oxygen on exterior surfaces.
11. Provide thorough, accurate, documentation.
    a. Keep accurate up-to-date records of what is actually built into the flight hardware.
    b. Avoid loose descriptions such as "Ethylene-propylene rubber" or even "Fluorocarbon elastomer per MIL-R-83248, Class 1, brown."
    c. Document and retain Waivers and Material Usage Agreements (MUA).

d. Make detailed photographic coverage accessible for the life of the spacecraft.

12. Verify design by a Systems Test covering nominal and off-nominal operation.

CUSTOMER'S ROLE

Other factors may directly or indirectly influence a possible in-flight spacecraft "event". These factors are, generally speaking, government-furnished items called GFE (Government Furnished Equipment) which are supplied to make the spacecraft more habitable, items of housekeeping such as food, clothing, hygiene, sleep, and recreation items.

Such things are, of course, necessary for human beings to survive and to be productive. And there aren't adequate substitutes for paper, for example, (for written instructions and other needs such as tissue paper), fabrics for clothing (and towels), food items, medical items, and the various maintenance items. So without non-flammable substitutes these items are carried with approval via a Material Usage Agreement (MUA).

TRADE-OFFS

The longer the space flight the more complex that area becomes. For example a decision has to be made on whether or not the crew should take sufficient socks and underwear to provide two changes of these garments per week discarding them after wear, or whether it is more effective to provide a washing machine and dryer so only a few items per person will suffice. A very long mission such as to Mars, taking about two and one-half years, or a lunar outpost to be manned for a substantial period of time will probably have such equipment as well as a trash compactor, some special food preparation equipment (such as a microwave oven with a food warmer and possibly a fry pan, a broiler, and a toaster), a hair dryer, and other such amenities, with the above list emphasizing those which can contribute to an accidental fire if misused or if various safeguards fail. In the realm of maintenance there is the heat gun, the soldering iron, and perhaps welding equipment if major spacecraft assembly is required. And regarding maintenance, there is the need to change filters at appropriate times, and to dispose of the filtered material safely.

Motor-driven items, in the early days when the atmosphere was pure oxygen, involved only iduction motors. But many off-the-shelf things such as a vacuum cleaner, electric drill, battery operated screwdrivers, or hair dryers come with motors which have brushes. These are an ignition source if in an environment containing a flammable gas mixture.

Most electric equipment is not built for use in a zero-gravity environment which may include large amounts of liquid condensate from spilled fluids. Again, in early designs, we have seen quantities of liquids appearing in various regions, from sources unknown, making the crew and ground controllers happy that total waterproofing had been part of the design. And so today, as we provide various electrical items, if coatings are not provided everywhere, and of a design which can survive the service life of the item, we are faced with electrical leakages which can become ignition sources.

Finally we have to consider garbage. We are world-famous in generating garbage on the ground. In flight we have what I consider a major problem, depending on how often the trash man comes by. If we get a crew transfer every four months, for example, that might mean many bags of mixed organic discards (food scraps, medical waste, packaging, etc.) which will develop offensive odors and toxic gases which are the result of biological action which is exothermic and which has been the cause of fires of "unknown" origin or, more properly, spontaneous ignition.

CONCLUSION

What all this says to me is that the designer has a major responsibility in making spacecraft fire-safe, but so has the customer. A comprehensive study clearly shows that the greatest probability of an accidental fire will most likely include GFE, and that area, therefore, is in greatest need of attention today. In view of all these considerations it appears to me that an integrated study of the final design is mandatory, and if conducted by a truly objective body can contribute to the reduction of fire hazards.

J. H. Kimzey,

Eagle Engineering
17 October 1991

A PERSPECTIVE ON
THE NASA FLAMMABILITY SCREENING TEXT

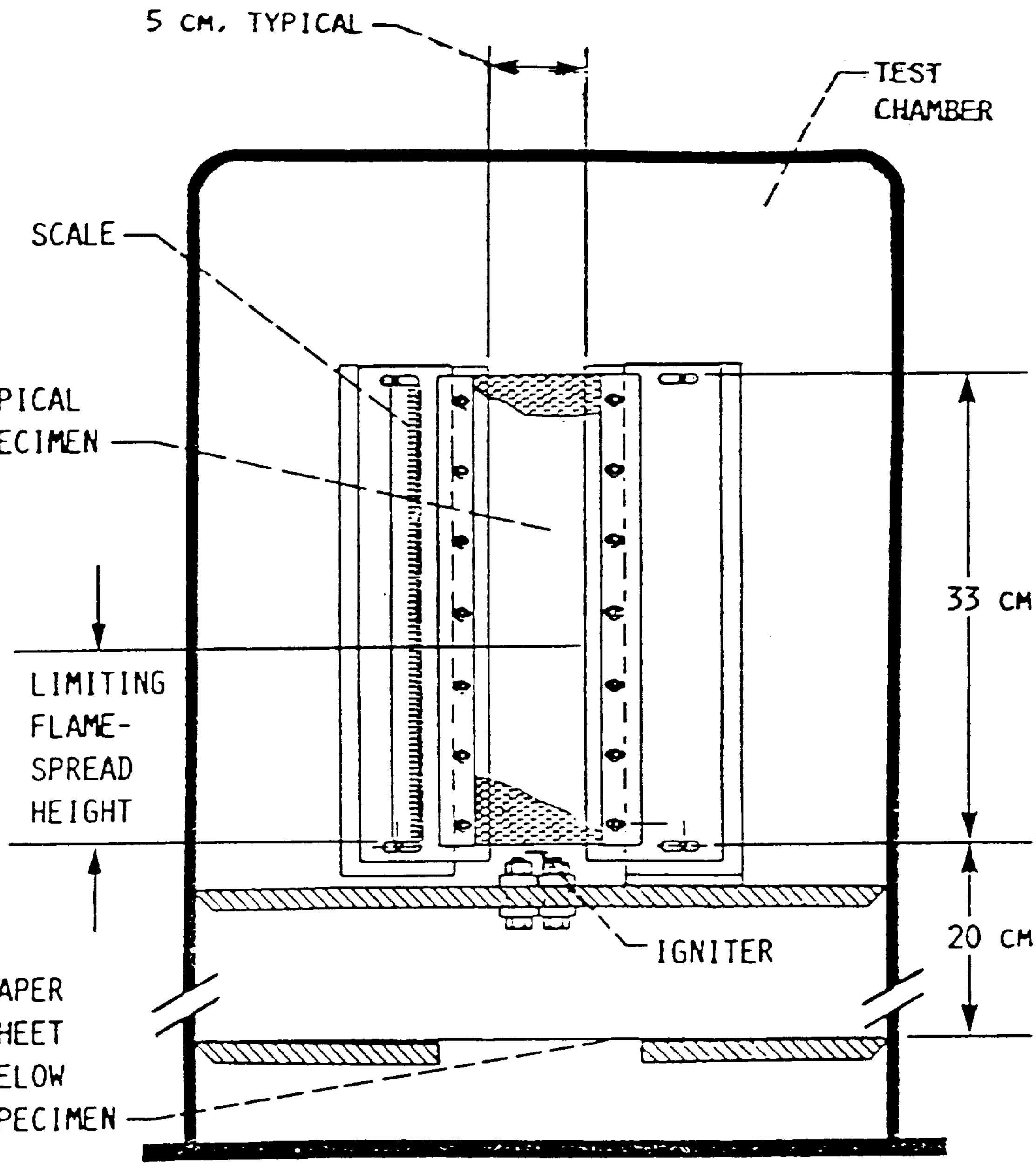
DESIGN TO CONTROL

- AN IGNITION SOURCE WILL ALWAYS EXIST AND A FIRE CAN START

- A FIRE MUST BE SELF-LIMITING WITHIN A SHORT DISTANCE FROM ITS IGNITION POINT

- EXPOSED MATERIALS SHALL BE SELF-EXTINGUISHING EITHER INHERENTLY OR IN CONFIGURATION;
  I.E., BY LIMITATION OF THE AMOUNT, SPACING, OR ACCESSIBILITY OF THE MATERIALS

T. Ohlemiller, NIST



- NASA IGNITER PROPERTIES:

  750 CALORIES 1100 CELSIUS

  6.4 CM FLAME HGT. 25 SECONDS

TEST AT WORST CASE THICKNESS AND AMBIENT OXYGEN LEVEL

QUESTIONS

IS NORMAL GRAVITY FLAMMABILITY ALWAYS GREATER THAN MICRO-GRAVITY FLAMMABILITY ?

IS NASA UPWARD SPREAD TEST A WORST CASE TEST FOR NORMAL GRAVITY FLAMMABILITY ?

T. Ohlemiller, NIST

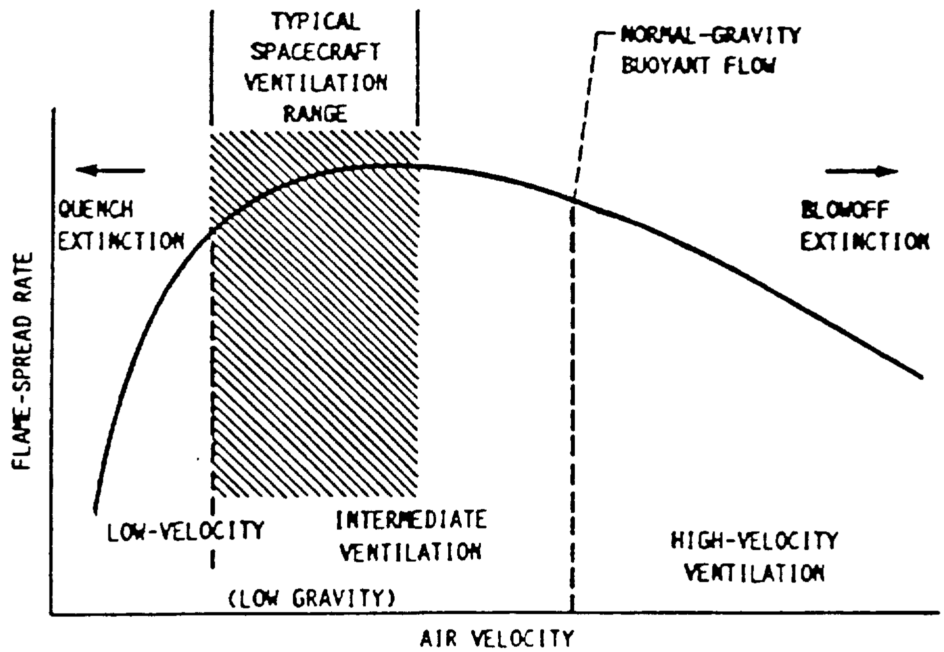


FIGURE 11. - EFFECT OF VENTILATION AIR FLOW ON FLAME-SPREAD RATE FOR THIN-PAPER SPECIMENS.

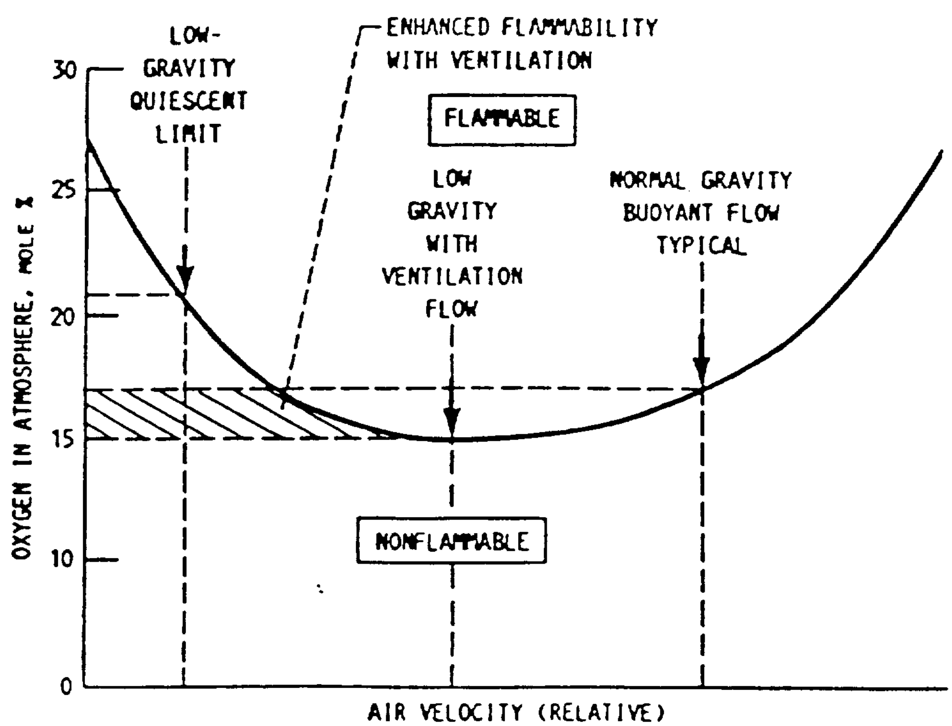


FIGURE 12. - FLAMMABILITY-LIMIT COMPARISON FROM DROP-TOWER LOW-GRAVITY DOWNWARD BURNING THIN-PAPER TESTS.

APPROACH:

COMPARE BEHAVIOR OF A SET OF MATERIALS IN NASA

TEST AND IN STANDARD NIST TESTS

OBTAIN A PERSPECTIVE ON WHAT IT MEANS TO

PASS NASA TEST AND LOOK FOR CORRELATION

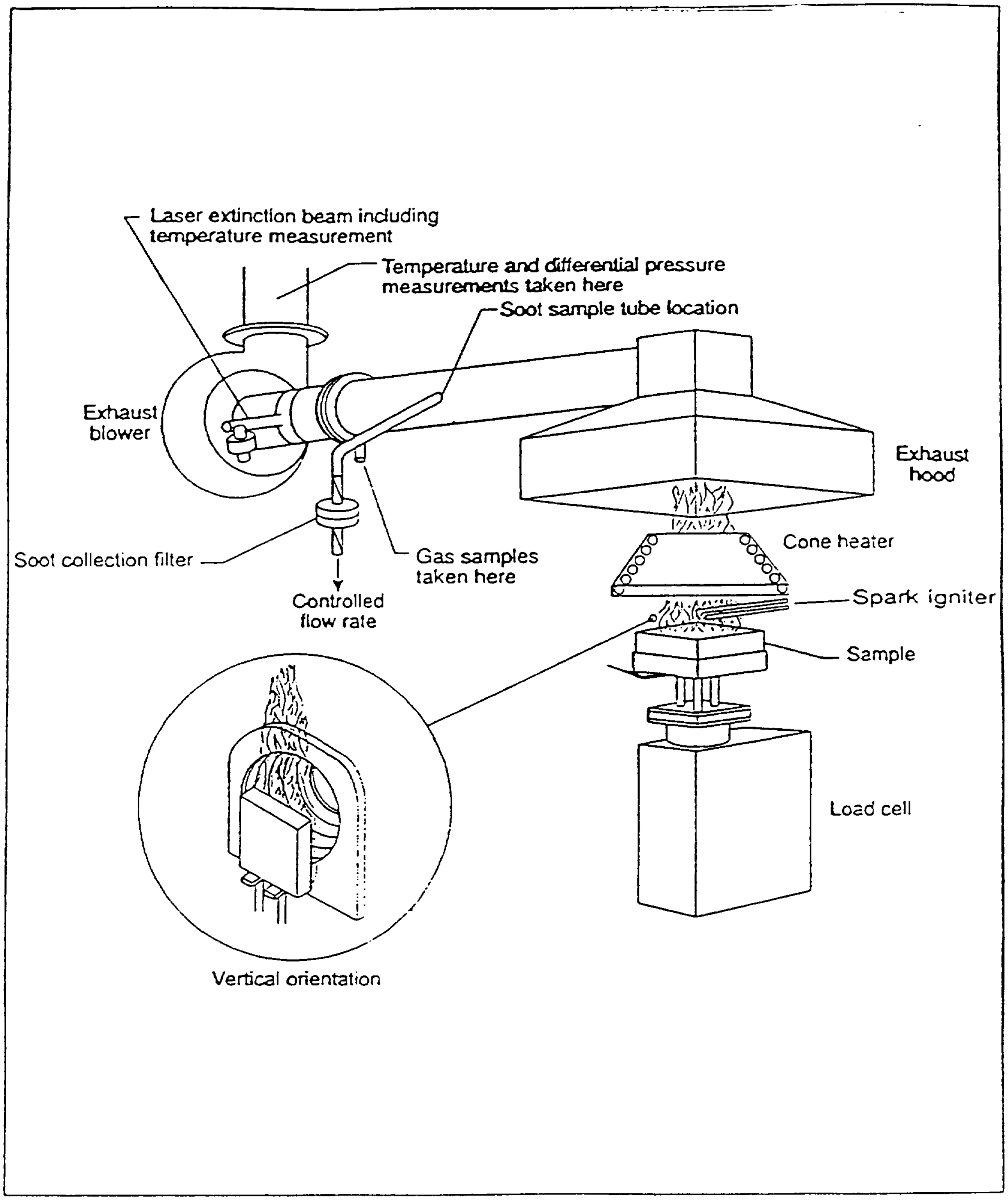
IN BEHAVIOR BETWEEN TWO TYPES OF TESTS

T. Ohlemiller, NIST

NIST TESTS

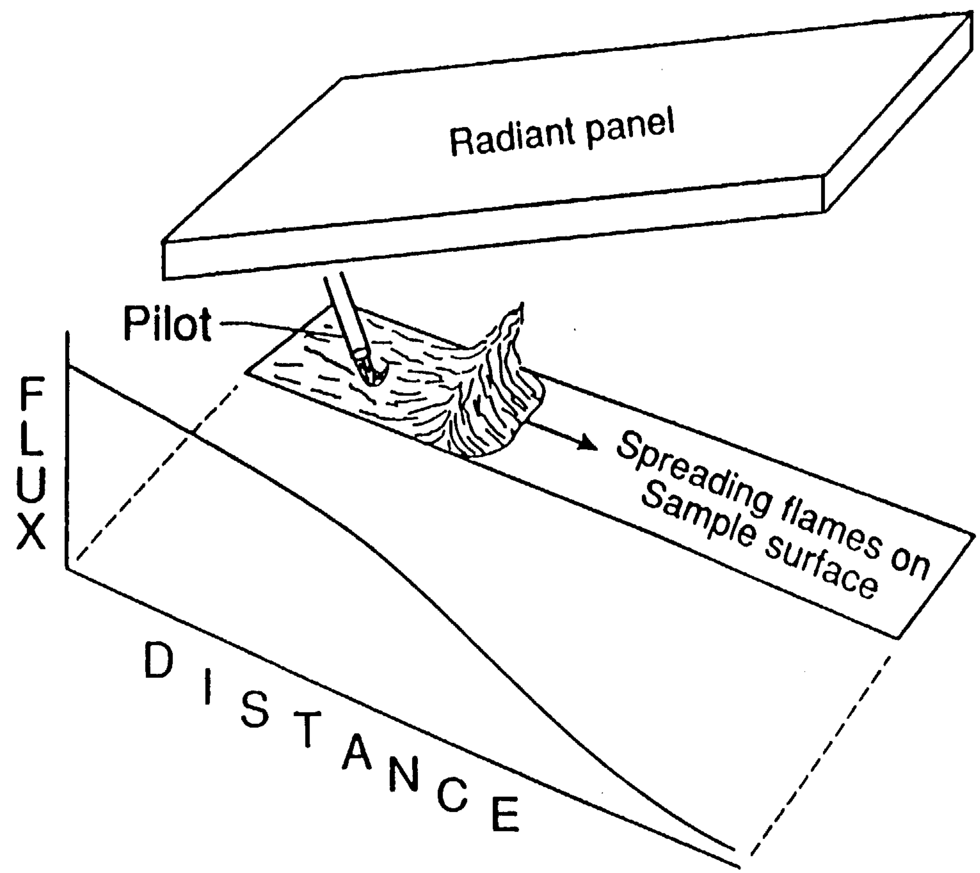
- IGNITION DELAY TIME AS A FUNCTION OF INCIDENT RADIANT HEAT FLUX
- RATE OF HEAT RELEASE AS A FUNCTION OF INCIDENT HEAT FLUX
- LATERAL FLAME SPREAD RATE AS A FUNCTION OF INCIDENT HEAT FLUX

T. Ohlemiller, NIST



Schematic of Cone Calorimeter

Lift Apparatus in Horizontal Orientation



Schematic of Lateral Ignition and Flame Spread (LIFT) test when sample is horizontal.

MATERIALS FOR NIST FLAMMABILITY TESTING

- -- PYRELL POLYURETHANE FOAM (FOAMEX, EDDYSTONE, PA.); 2.54 CM THICK

- -- COTTON TOWELLING; 86% COTTON/14% POLYESTER (DUNDEE MILLS, GRIFFIN GA.); ≈ 7 mm thk.

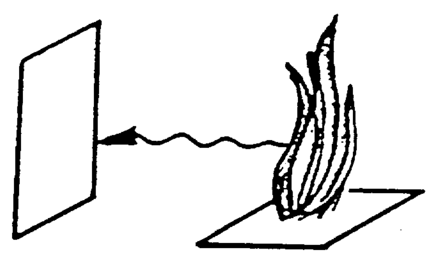
- -- LEXAN POLYCARBONATE SHEET (GENERAL ELECTRIC)

  - -- 9034, UNRETARDED; 1.6 mm THK

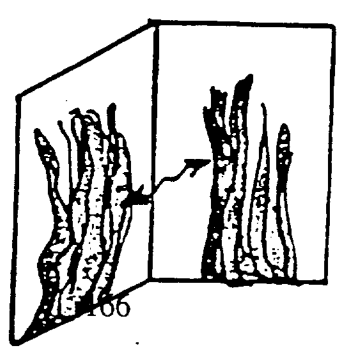
  - -- 9600, RETARDED; 1.6 mm THK.

SOURCES OF "EXTERNAL" RADIATION

NEARBY BURNING OBJECT:



SELF-FEEDBACK:



T. Ohlemiller, NIST

MATERIALS FOR PHASE 2 OF STUDY

-- COTTON TOWELLING (COTTON/POLYESTER); ≈ 7 MM THK.

-- LEXAN 9034 POLYCARBONATE; 1.6 MM THK.

-- NOMEX POLYAMIDE CLOTH; 6.8 OZ/YD^2

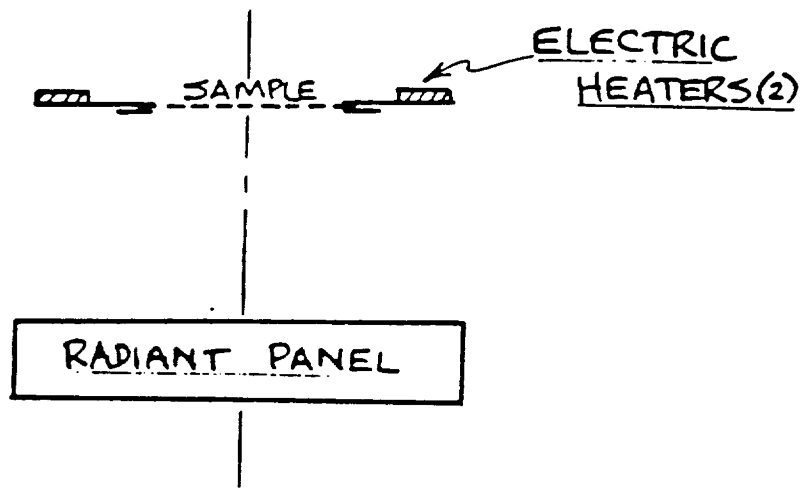
-- FLAME RETARDED COTTON CLOTH; 6.0 OZ/YD^2

-- EPOXY/GLASS CIRCUIT BOARD; 1.6 MM THK.

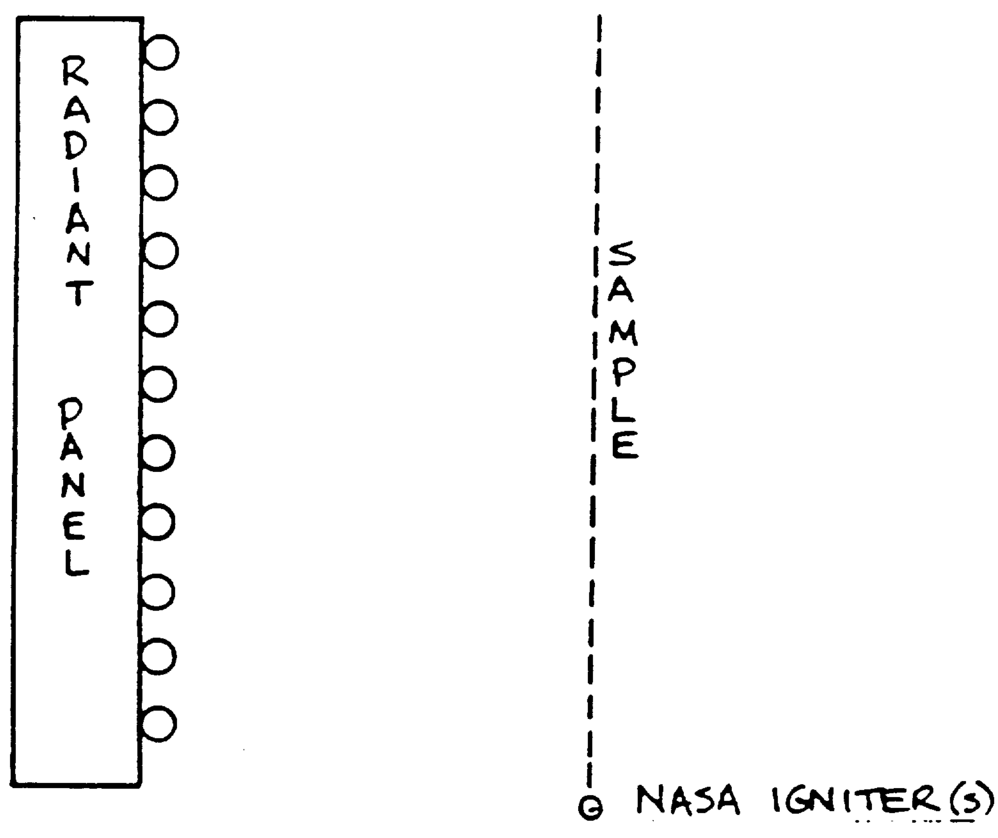
-- KYDEX PVC/ABS BLEND; 1.6 MM THK

PRE-HEATED NASA TEST

TOP:



SIDE, SECTION:



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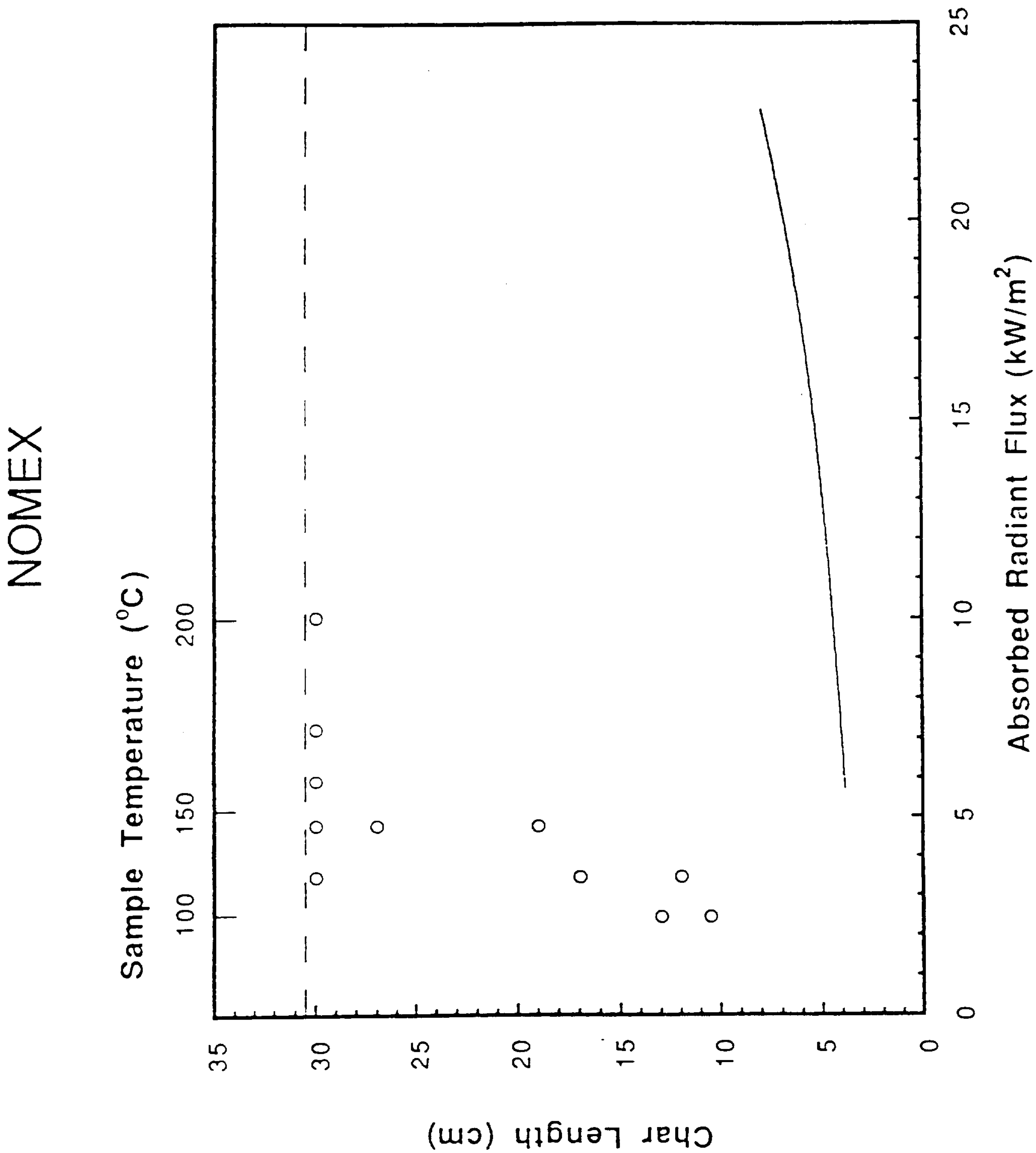
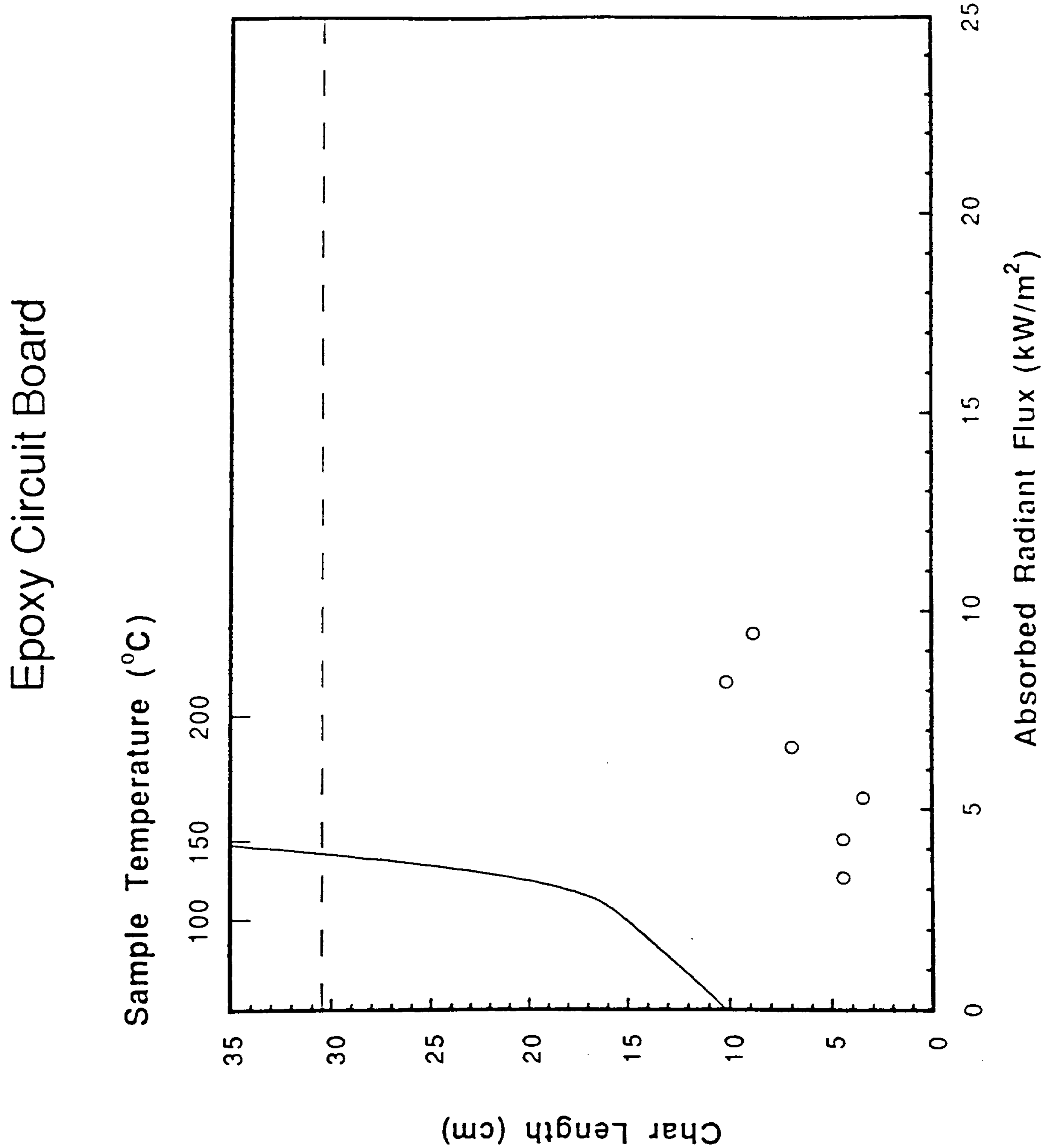
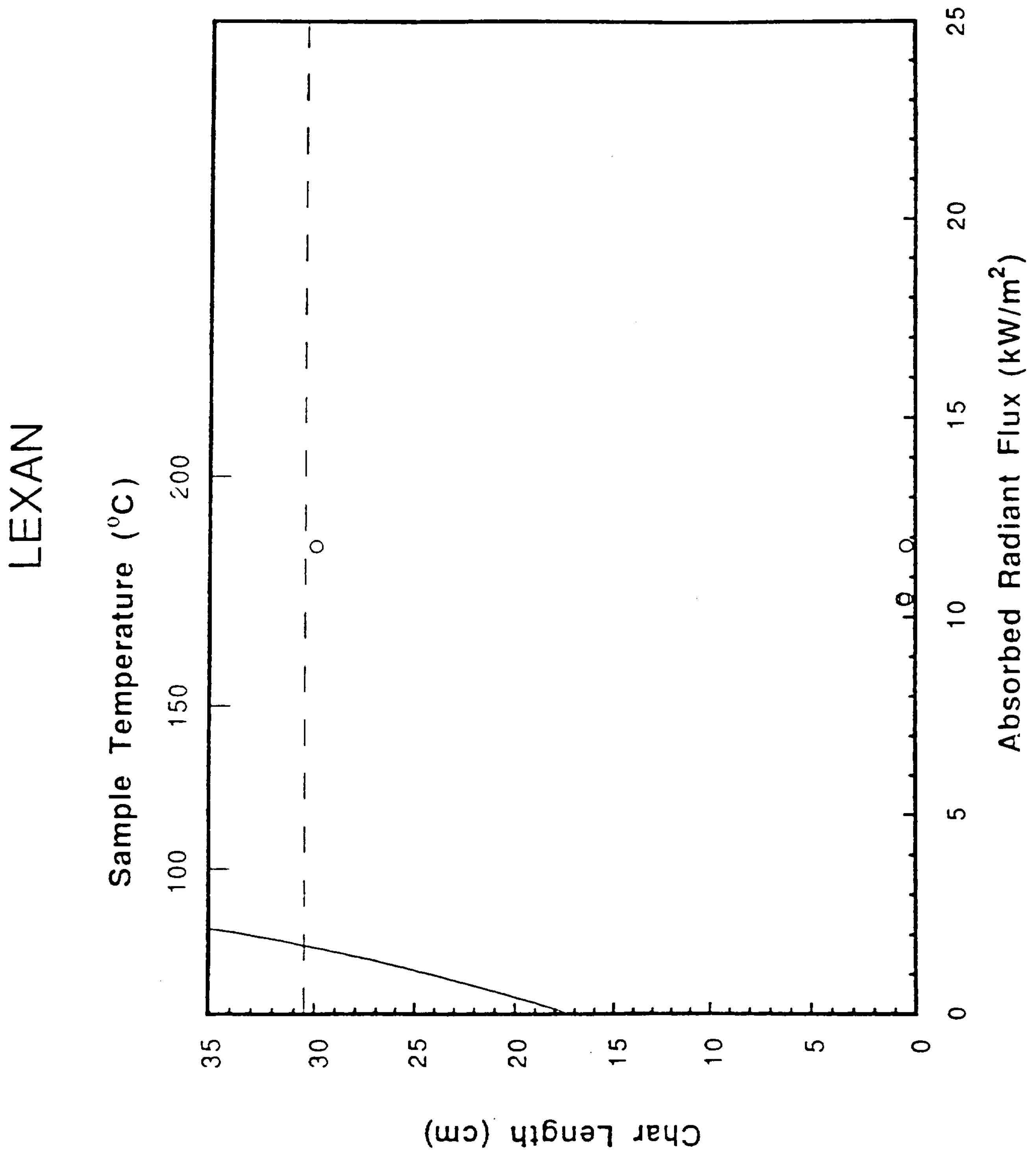


T. Ohlemiller, NIST


Epoxy Circuit Board
Sample Temperature (^oC)
100
150
200
Char Length (cm)
35
30
25
20
15
10
5
0
Absorbed Radiant Flux (kW/m^2)
0
5
10
15
20
25



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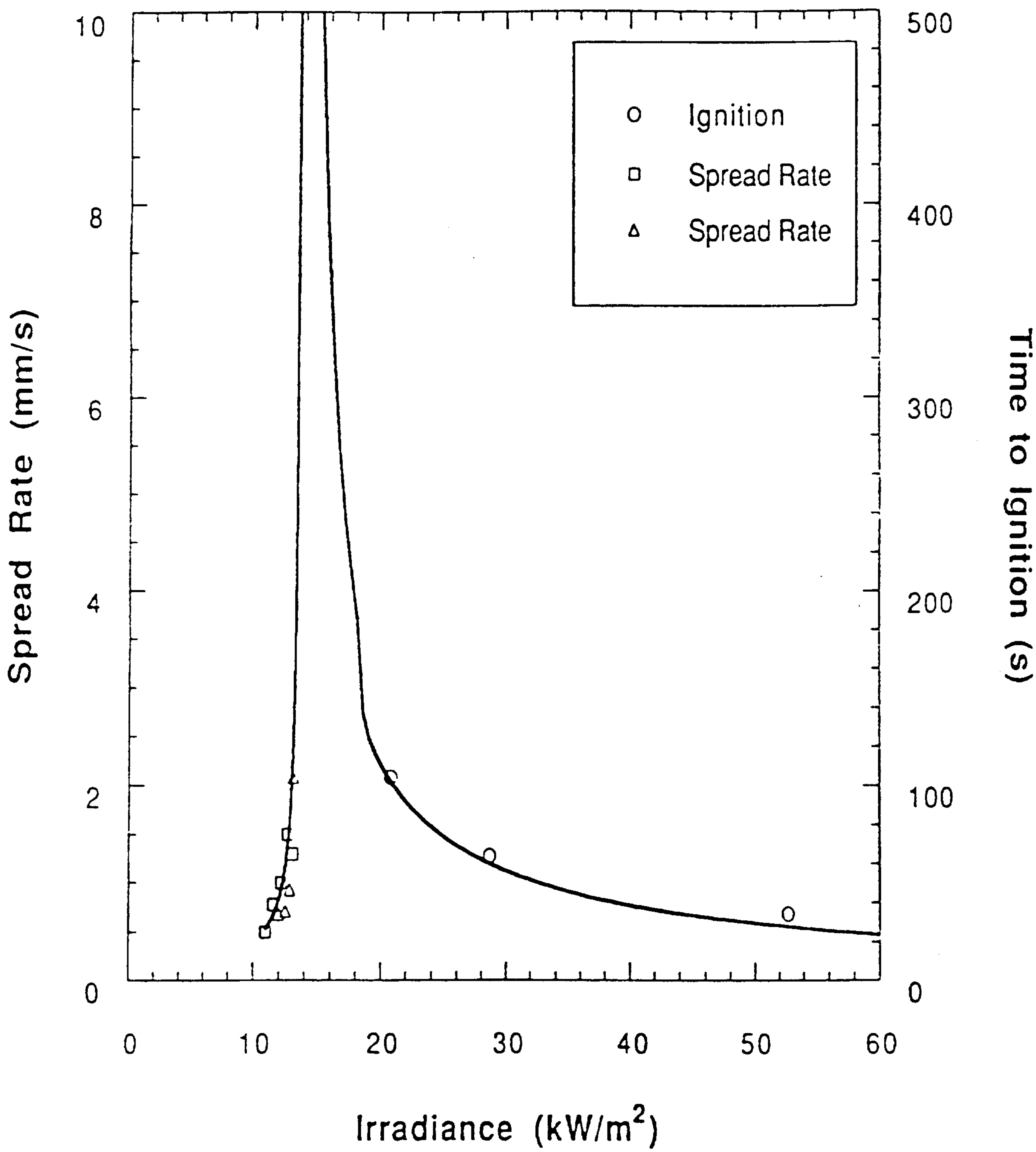
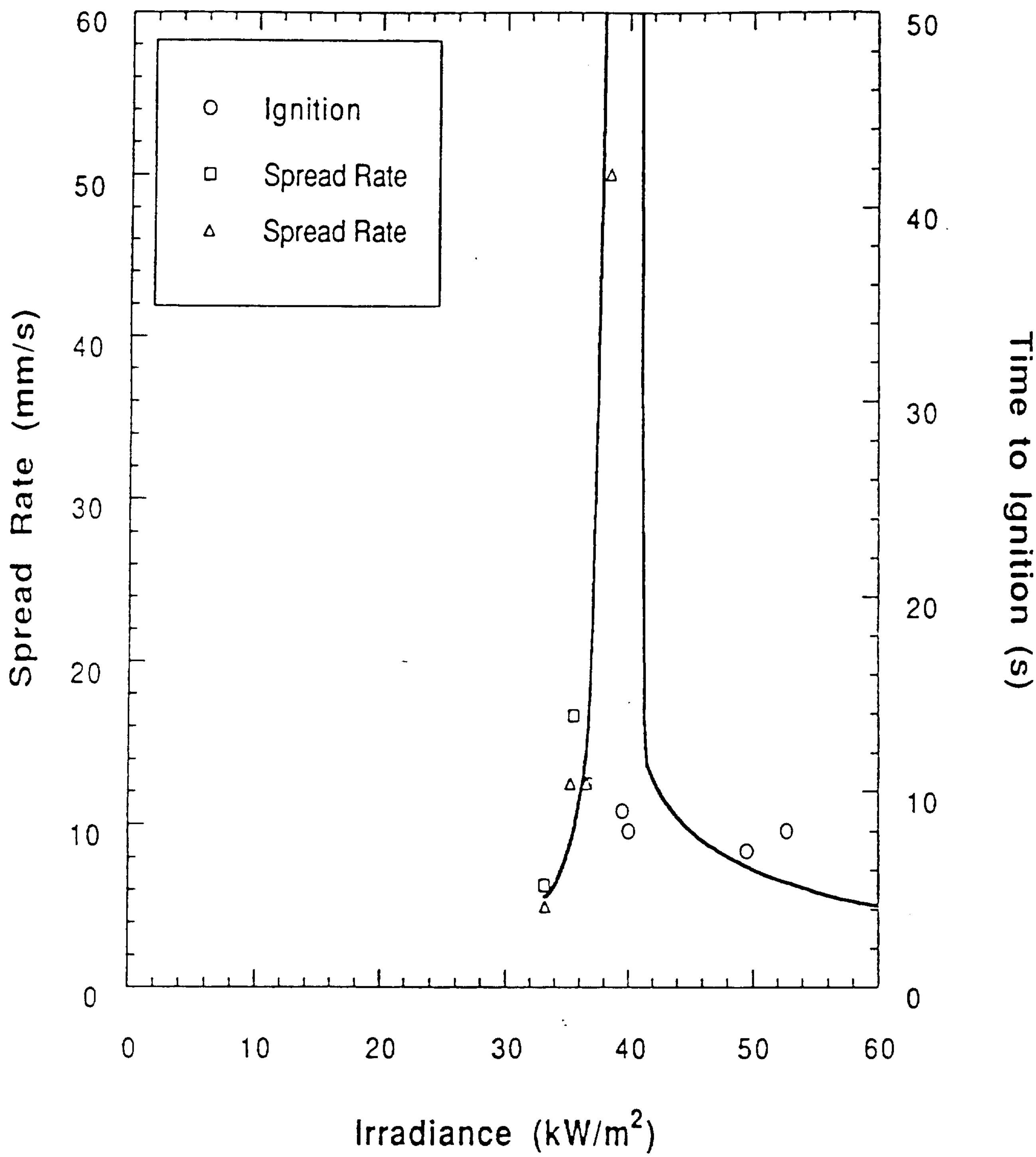
EPOXY/GLASS



Ignition
Spread Rate
Spread Rate
Spread Rate (mm/s)
Time to Ignition (s)
Irradiance (kW/m²)
0
2
4
6
8
10
0
100
200
300
400
500
0
10
20
30
40
50
60

NOMEX



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PLYWOOD, PLAIN (1.27cm)

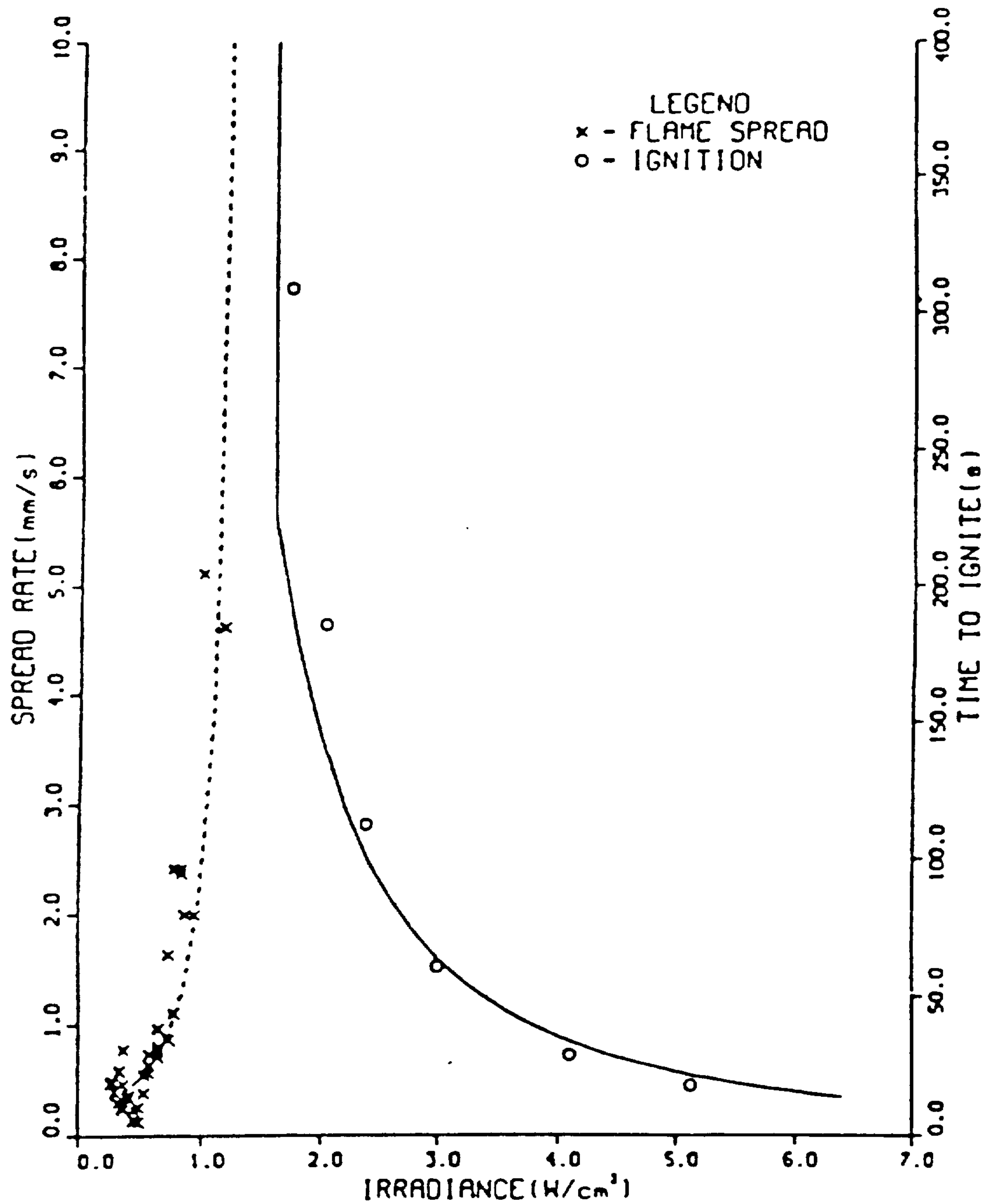

FIG. 12—*Spread and ignition results for plywood.*

SUMMARY / CONCLUSIONS

- MATERIALS PASSING THE NORMAL NASA TEST ARE FLAMMABLE, EVEN IN AIR, IF SUBJECTED TO VARYING AMOUNTS OF INCIDENT RADIATION.

- NIST TESTS PROVIDE A MORE COMPLETE, QUANTITATIVE PICTURE OF THIS FLAMMABILITY BUT IT CANNOT PRESENTLY BE RELATED TO NASA UPWARD FLAME SPREAD BEHAVIOR.

- PRE-HEATING A MATERIAL OFFERS A RELEVANT QUANTITATIVE MEASURE OF CONDITIONS THAT WILL YIELD UPWARD FLAME SPREAD.

- THERE IS A NEED TO "CALIBRATE" THE RELATION BETWEEN PRE-HEATED FLAMMABILITY ENHANCEMENT AND RADIATIVE SELF-FEEDBACK ENHANCEMENT.

T. Ohlemiller, NIST

RECOMMENDATIONS

- NASA CONSIDER ADOPTING A MODIFIED VERSION OF ITS STANDARD TEST THAT INCORPORATES RADIATIVE PRE-HEATING. APPLY AS A SUPPLEMENTAL TEST TO MATERIALS THAT ARE PRESENT ABOVE SOME THRESHOLD LEVEL.

- PURSUE THE ISSUE OF NORMAL GRAVITY VS. MICRO-GRAVITY FLAMMABILITY ON A MUCH MORE EXTENSIVE SCALE THAN AT PRESENT.

T. Ohlemiller, NIST

GRAVITY EFFECTS ON SMOLDERING OF POLYURETHANE FOAM

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University of California
Berkeley, CA 94720

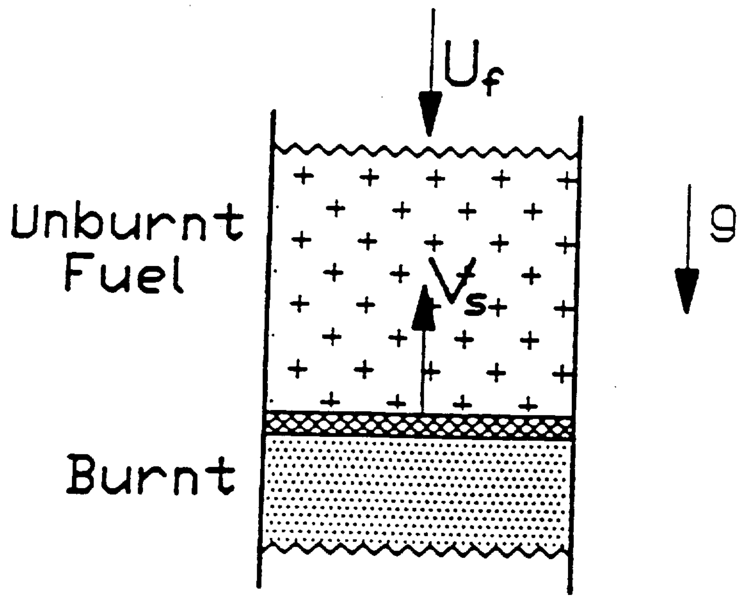
Work sponsored by NASA under Grant #NAG3-1252

SCIENTIFIC BACKGROUND

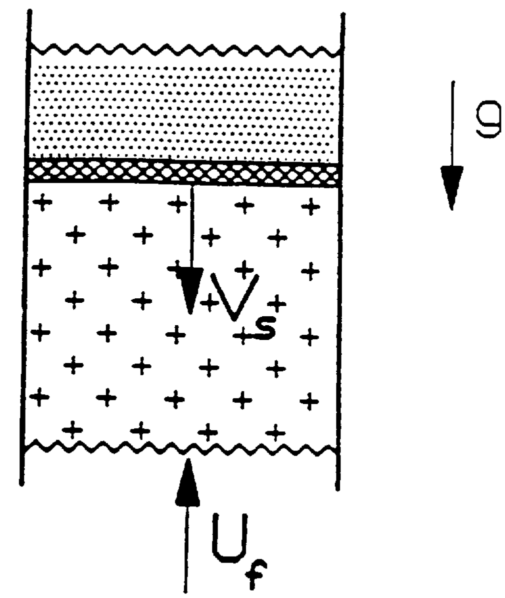
- Smoldering takes place in porous combustible materials, and is characterized by a non-flaming surface combustion reaction that propagates through the material interior.

- The propagation of the smolder reaction is controlled by the transfer of heat from the reaction zone to the virgin material, and the transport of oxidizer to the reaction zone, which is often limiting in smoldering.

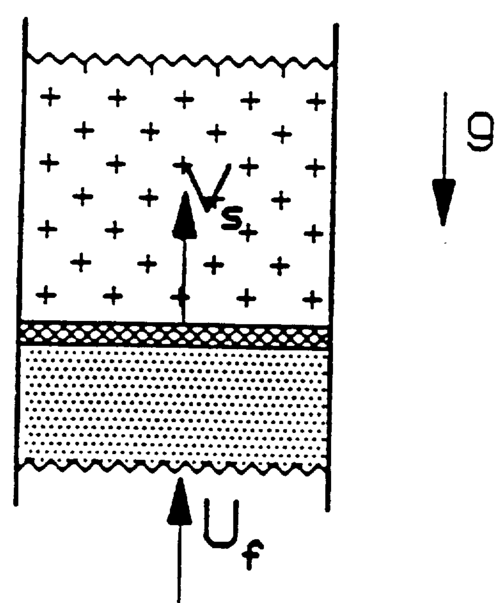
- The transition from the surface reaction (smoldering) to a gas-phase reaction (flaming) is also an important aspect of the problem.



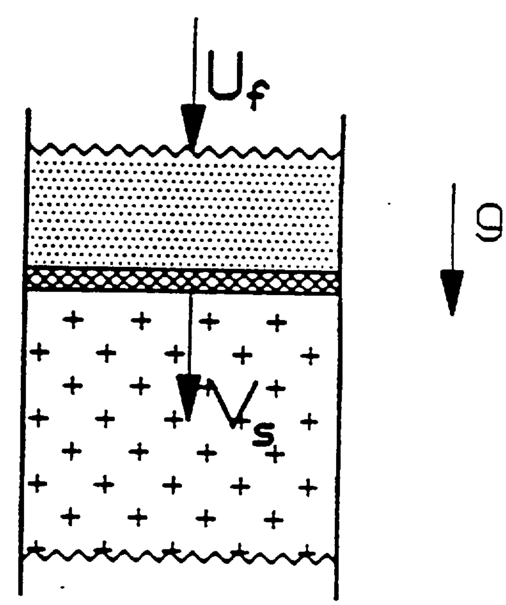
Co-current (opposed)
Upward



Co-current (opposed)
Downward



Counter-current
(flow-assisted)
Upward



Counter-current
(flow-assisted)
Downward

SCIENTIFIC IMPORTANCE OF EXPERIMENT

- Smolder important as a fire safety problem - Transition to flaming.

- Microgravity introduces questions about the transport of oxygen to the reaction zone (diffusion) and transfer of heat from the reaction zone (conduction).

- It appears that oxygen contained in porous fuel is sufficient to sustain smolder (diffusion of oxygen may be unimportant).

- In microgravity conduction of heat is the only transfer mechanism. (Still air good insulator.)

EXPECTED SMOLDER BEHAVIOR IN MICRO-GRAVITY

- Micro-gravity will eliminate convection, thus increasing the insulation of the fuel but also reducing the oxidizer transport. The increase in insulation will aid the smoldering process, flaming may occur in the area near the ingiter, mainly in the zones more exposed to the outside. So if flaming can occur it is more likely to occur at the beginning of the experiment and be visible. We are not sure if diffusion can transport enough oxidizer for flaming to occur.

- Ground-based experiments seem to indicate that transport by diffusion may be enough for smoldering to occur. The oxidizer inside the high void fractio fuel (97.5%) aided by the oxygen diffused from the ambient seem to be enough to sustain smoldering. Because of the decrease in the heat losses, we expect a steady self-sustained (but weak due to very restricted oxygen supply) smoldering. The velocity of the smoldering front should be of the order of 0.02 mm/sec.

Outline

- Background on Smoldering
- Normal gravity experiments
    - Opposed smoldering
    - Forward smoldering
- Drop-Tower micro-gravity experiments
    - Smolder ignition
- KC-135 - variable gravity experiments
    - Smolder near an interface
    - Opposed smoldering

Torero et al
Figure 1

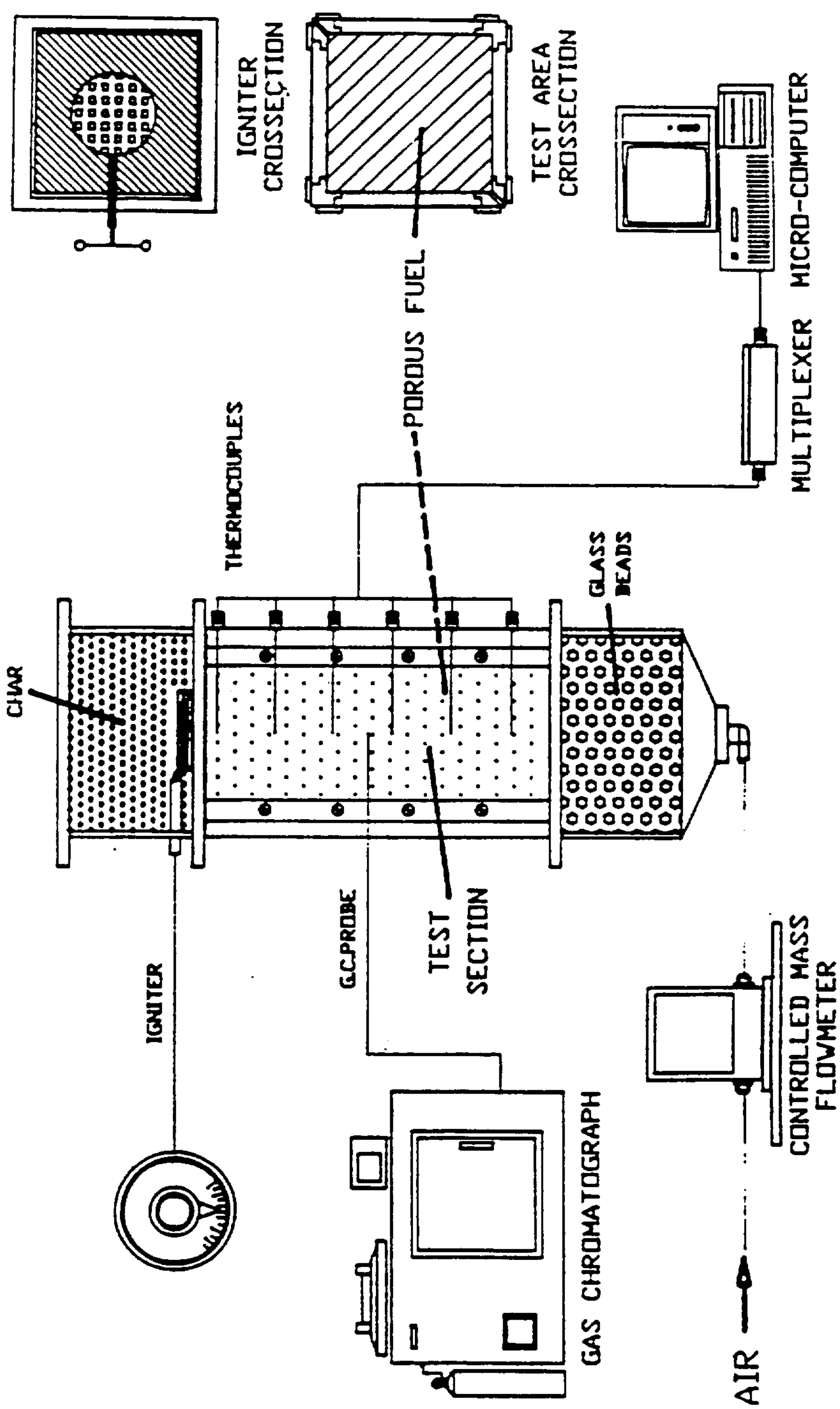
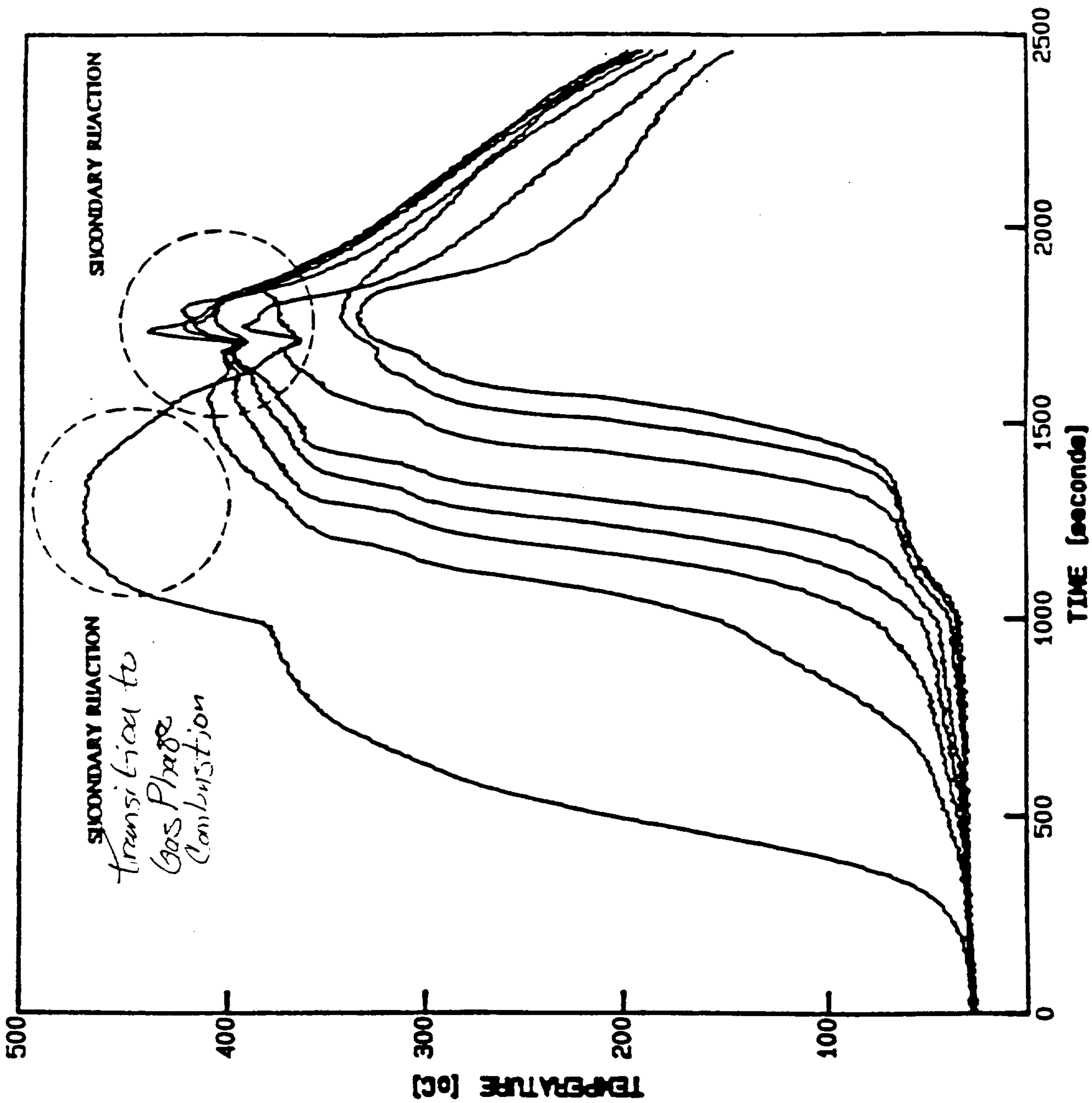
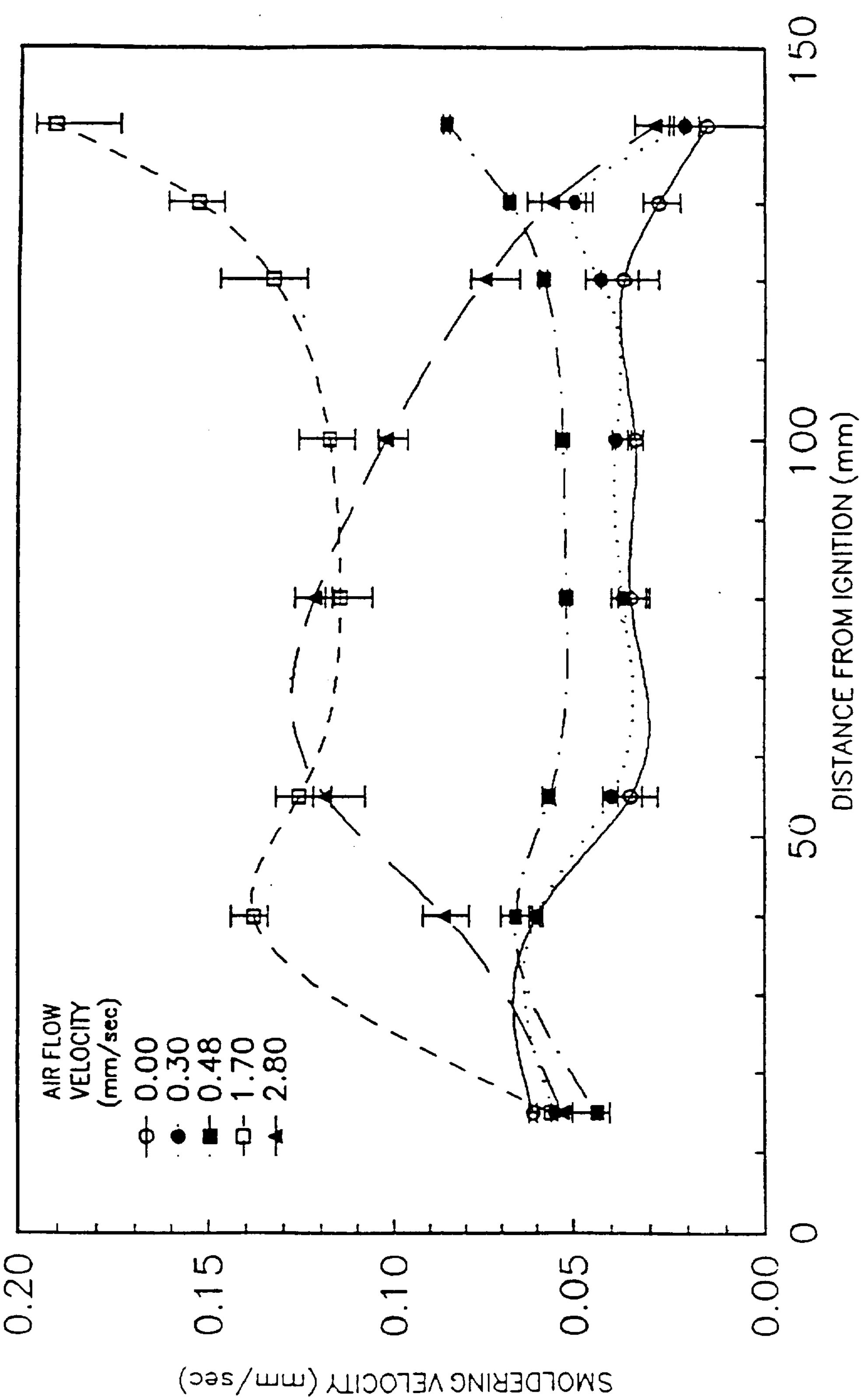
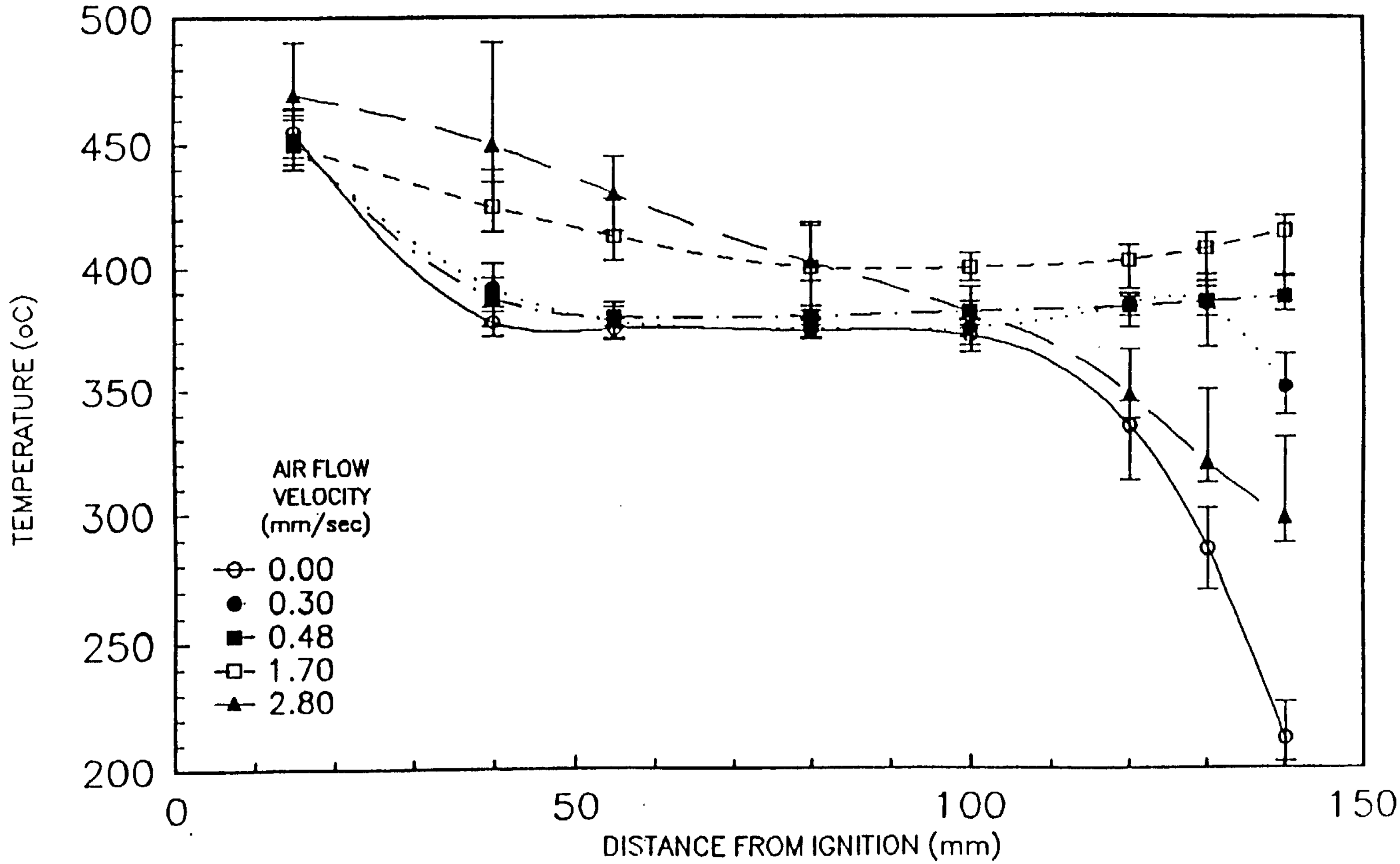


FIGURE 10

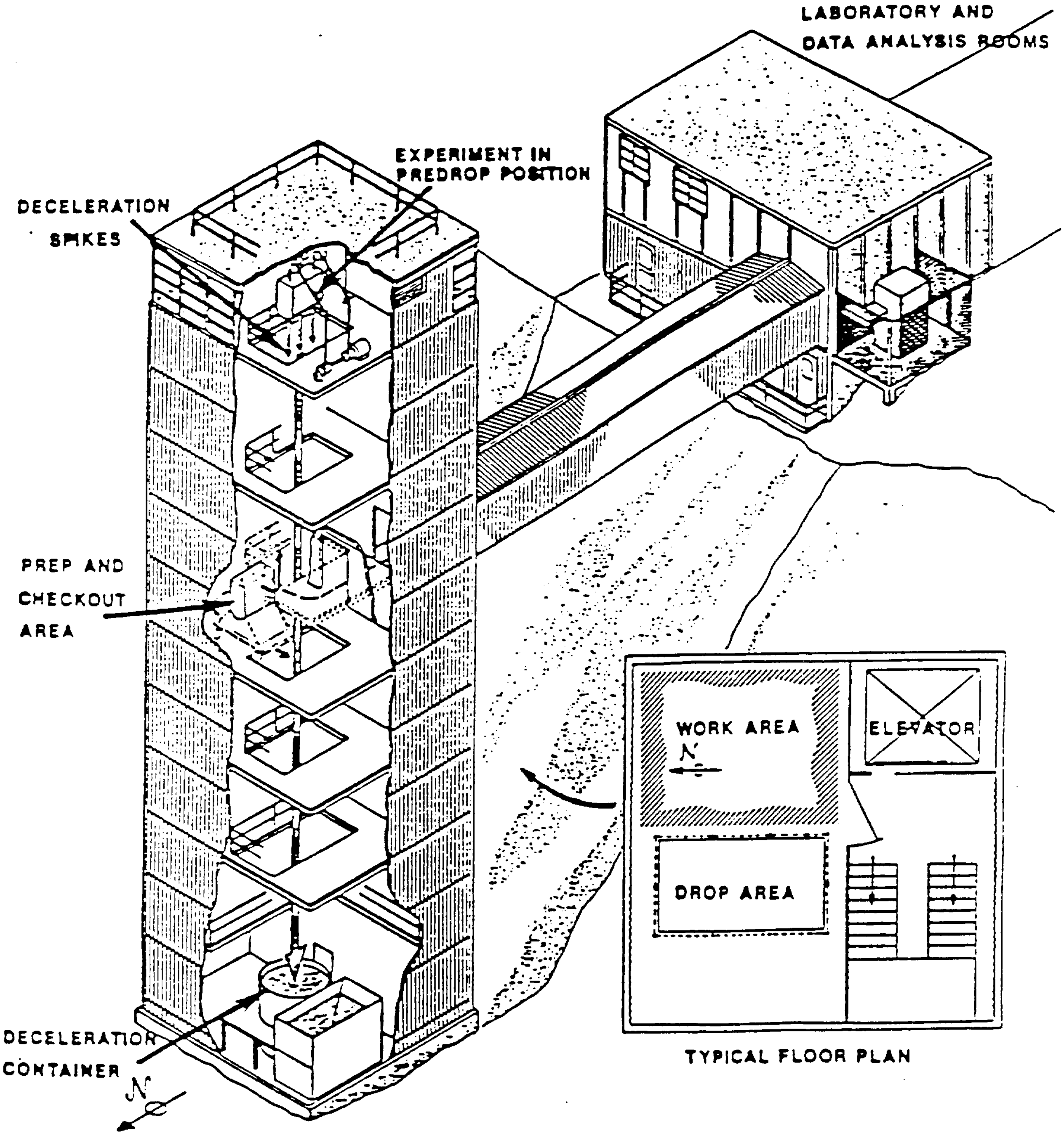


C. Fernandez-Pello, UC Berkeley


AIR FLOW
VELOCITY
(mm/sec)
0.00
0.30
0.48
1.70
2.80
0
50
100
150
DISTANCE FROM IGNITION (mm)
0.00
0.05
0.10
0.15
0.20
SMOLDERING VELOCITY (mm/sec)


TEMPERATURE (oC)
500
450
400
350
300
250
200
0
50
100
150
DISTANCE FROM IGNITION (mm)
AIR FLOW
VELOCITY
(mm/sec)
0.00
0.30
0.48
1.70
2.80

LEWIS RESEARCH CENTER 2.2 SECOND DROP TOWER



TOWER: 6.4 meters (21 ft) square by 30.5 meters (100 ft) tall

DROP AREA: 27 meters (89 ft) tall and cross section of 1.5 by 2.75 meters (5 by 9 ft)

RECOVERY SYSTEM: 2.2 meter (7 ft) deep container with sand

GRAVITATIONAL ACCELERATION: 10^{-5}g's for 2.2 seconds

Figure 5

C. Fernandez-Pello, UC Berkeley

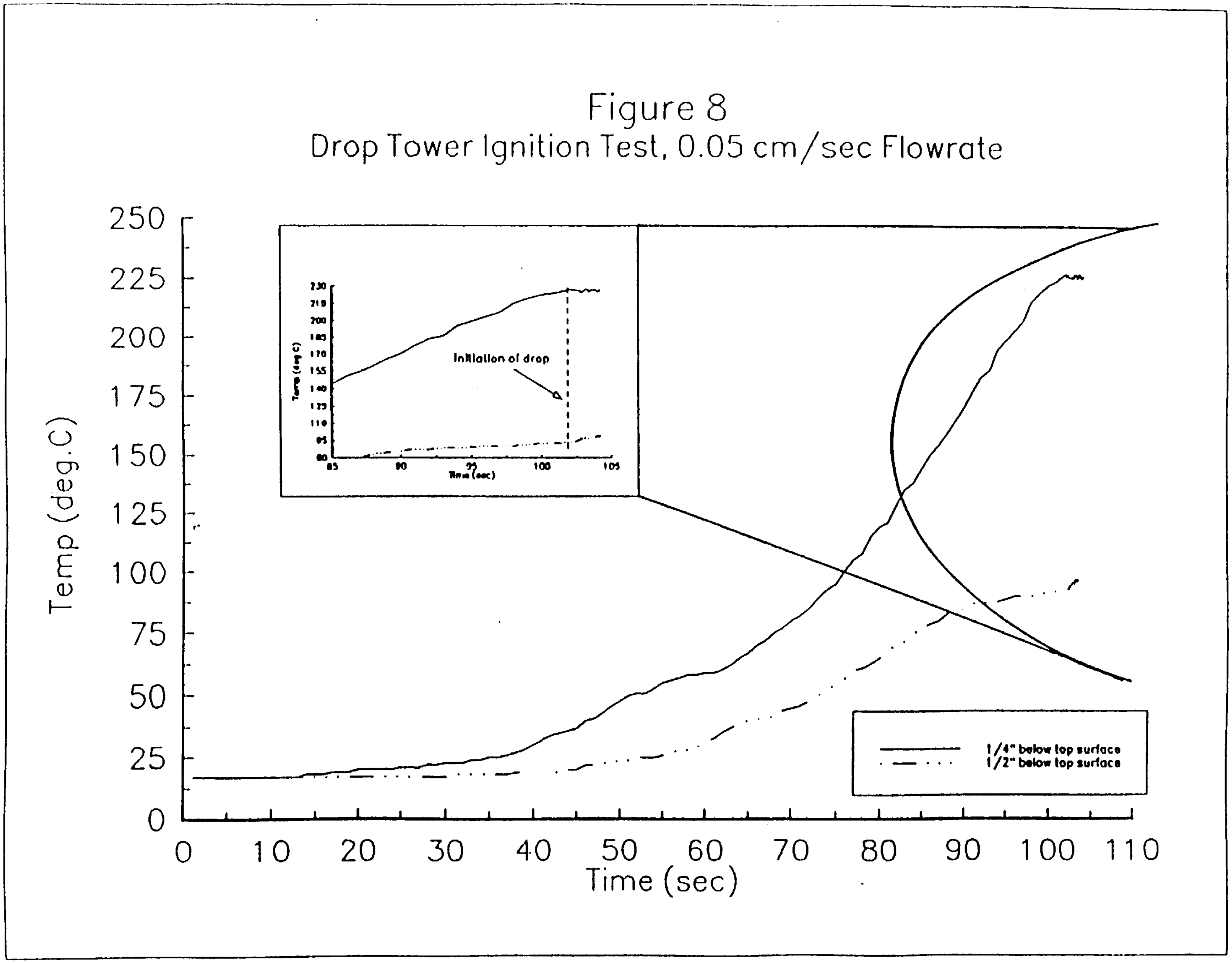
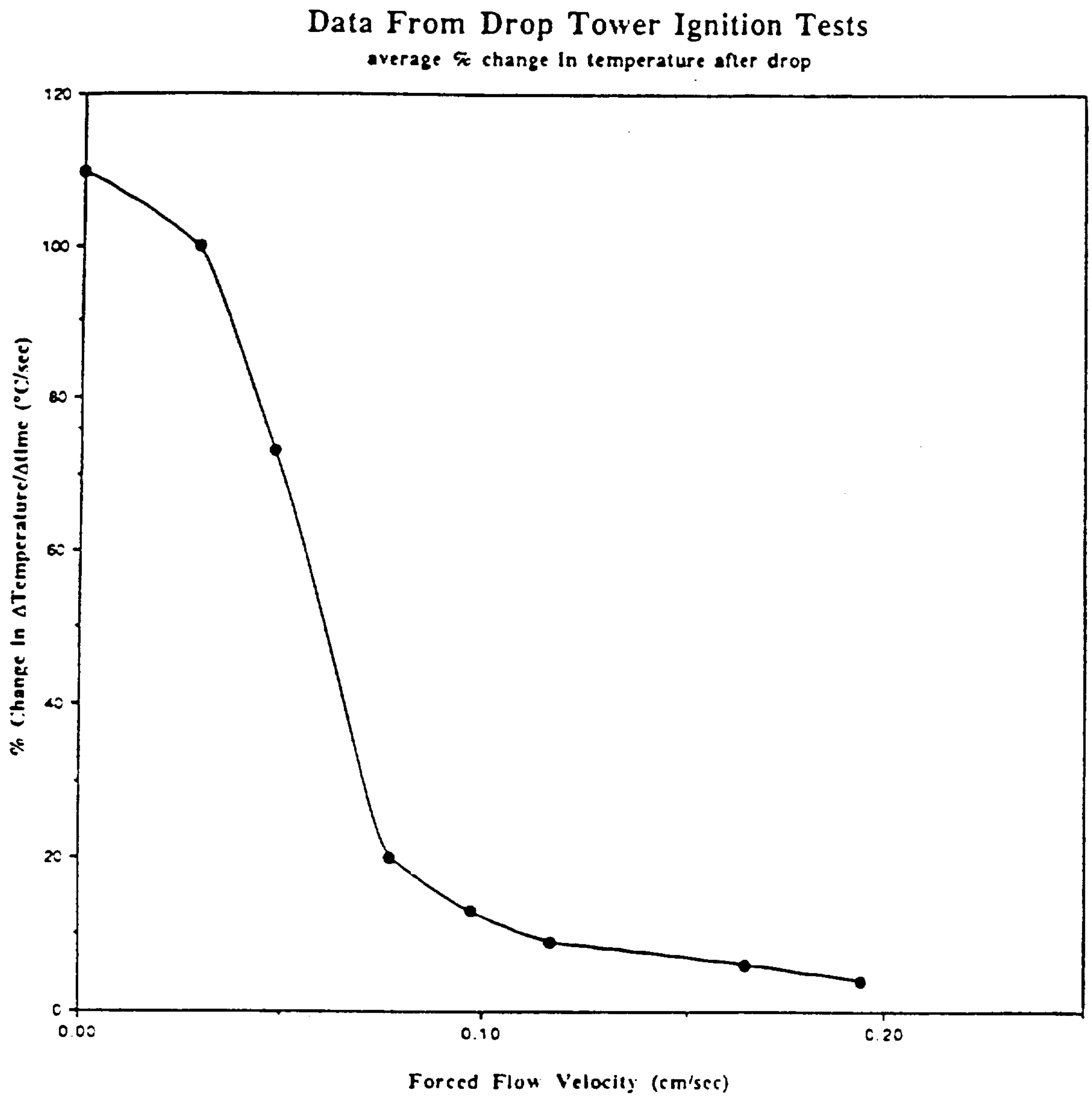


Figure 8 - Representative graph of temperature vs. time for a single drop. Flow rate was 0.05 cm/sec. Note that the upper temperature drops and the lower rises



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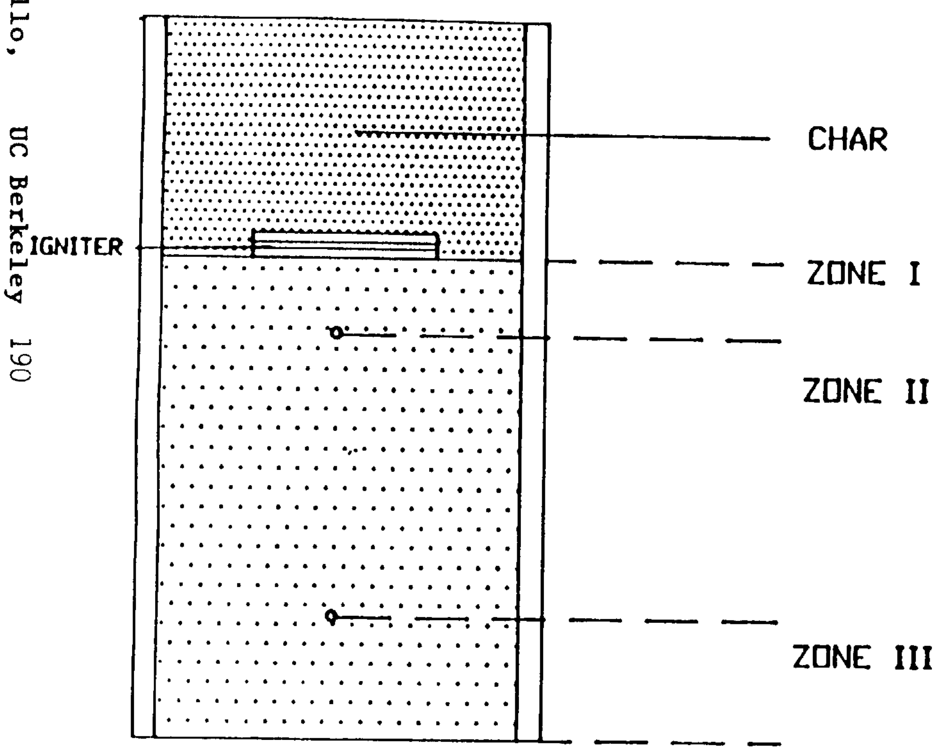
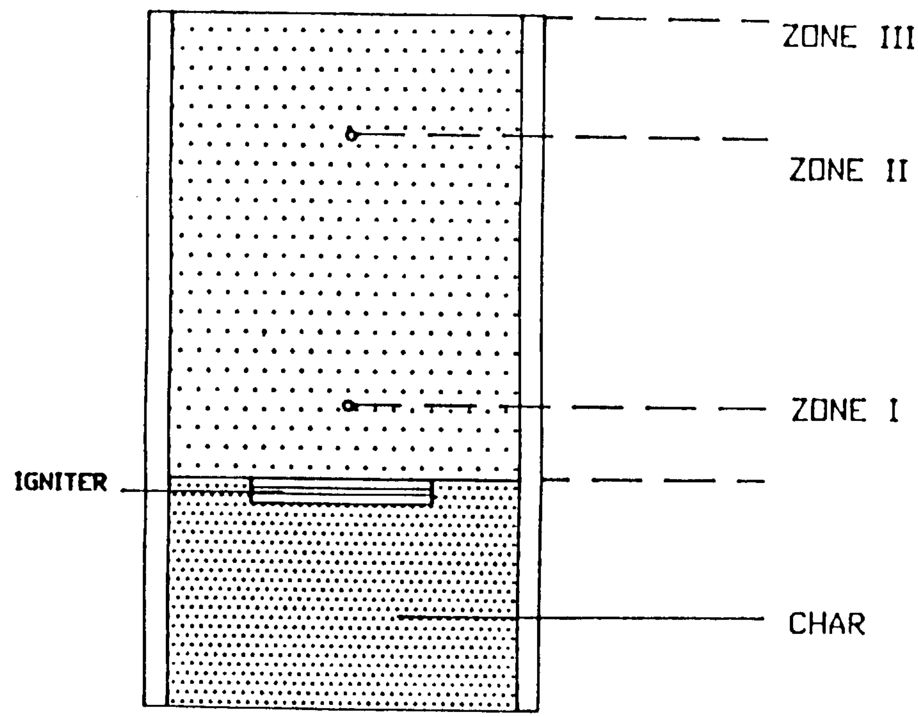
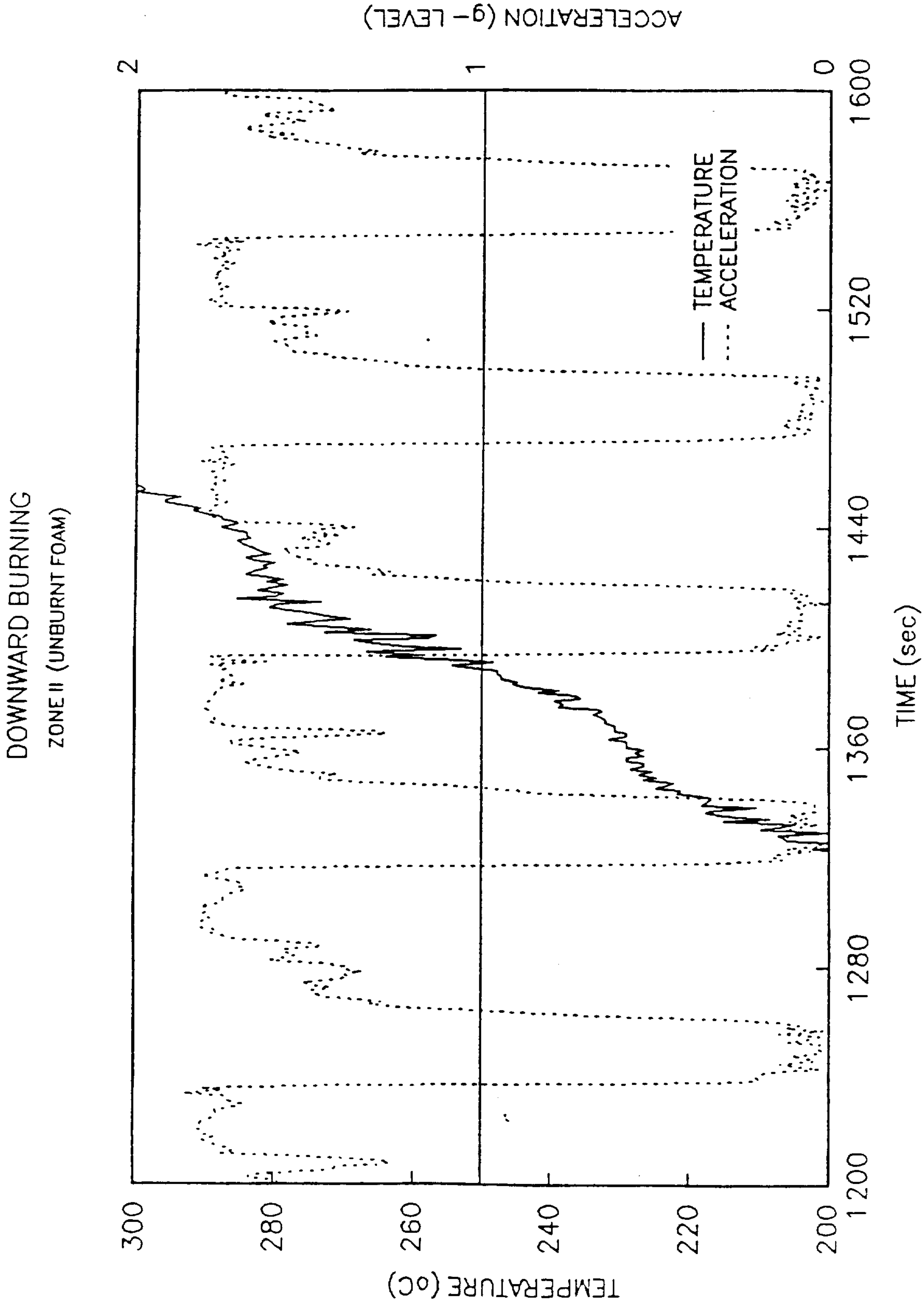
FORWARD DOWNWARD SMOLDERING

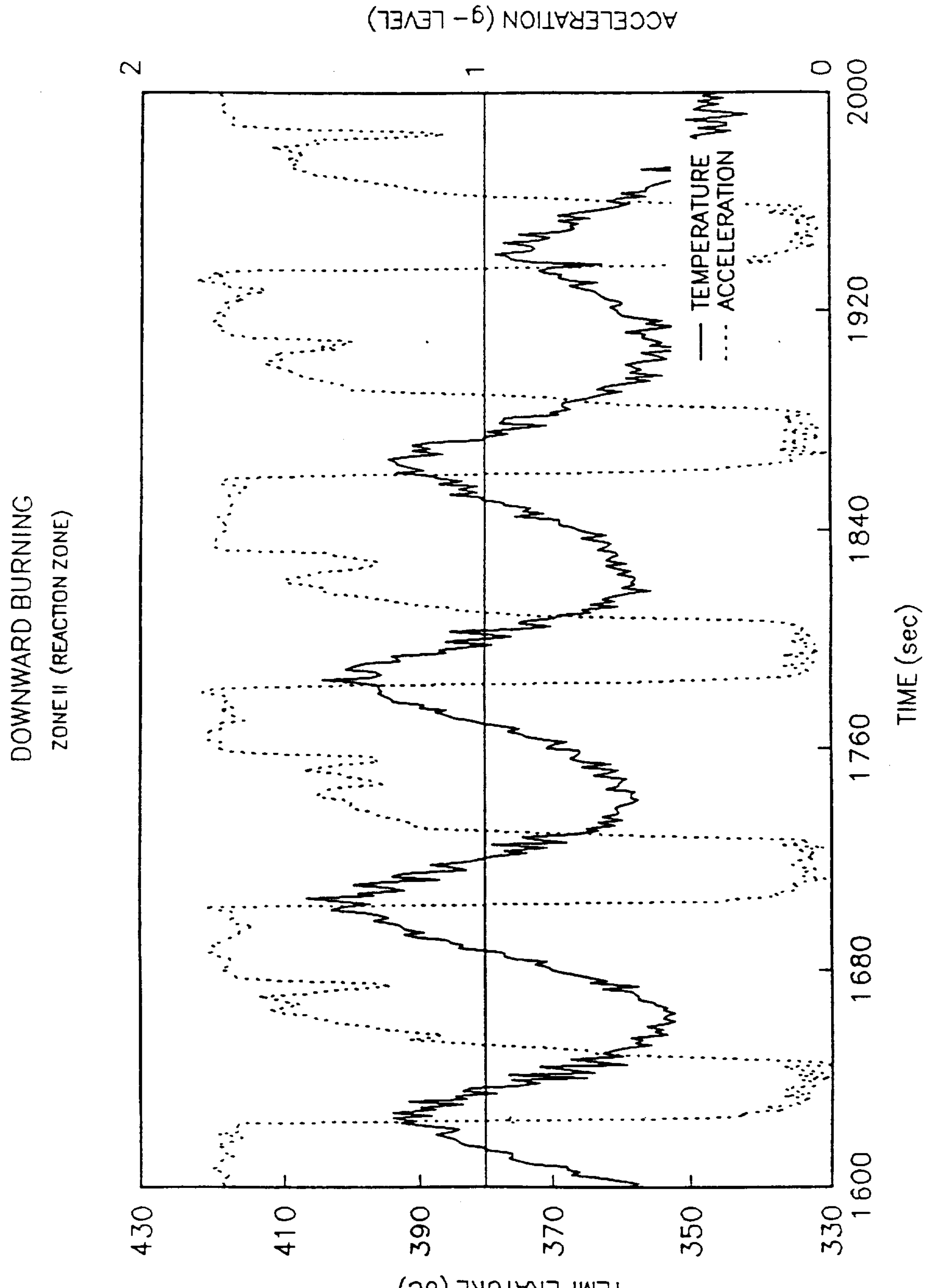


FORWARD UPWARD SMOLDERING





DOWNWARD BURNING
ZONE II (UNBURNT FOAM)
TEMPERATURE
ACCELERATION
TIME (sec)
1200
1280
1360
1440
1520
1600
TEMPERATURE (oC)
300
280
260
240
220
200
ACCELERATION (g– LEVEL)
2
1
0



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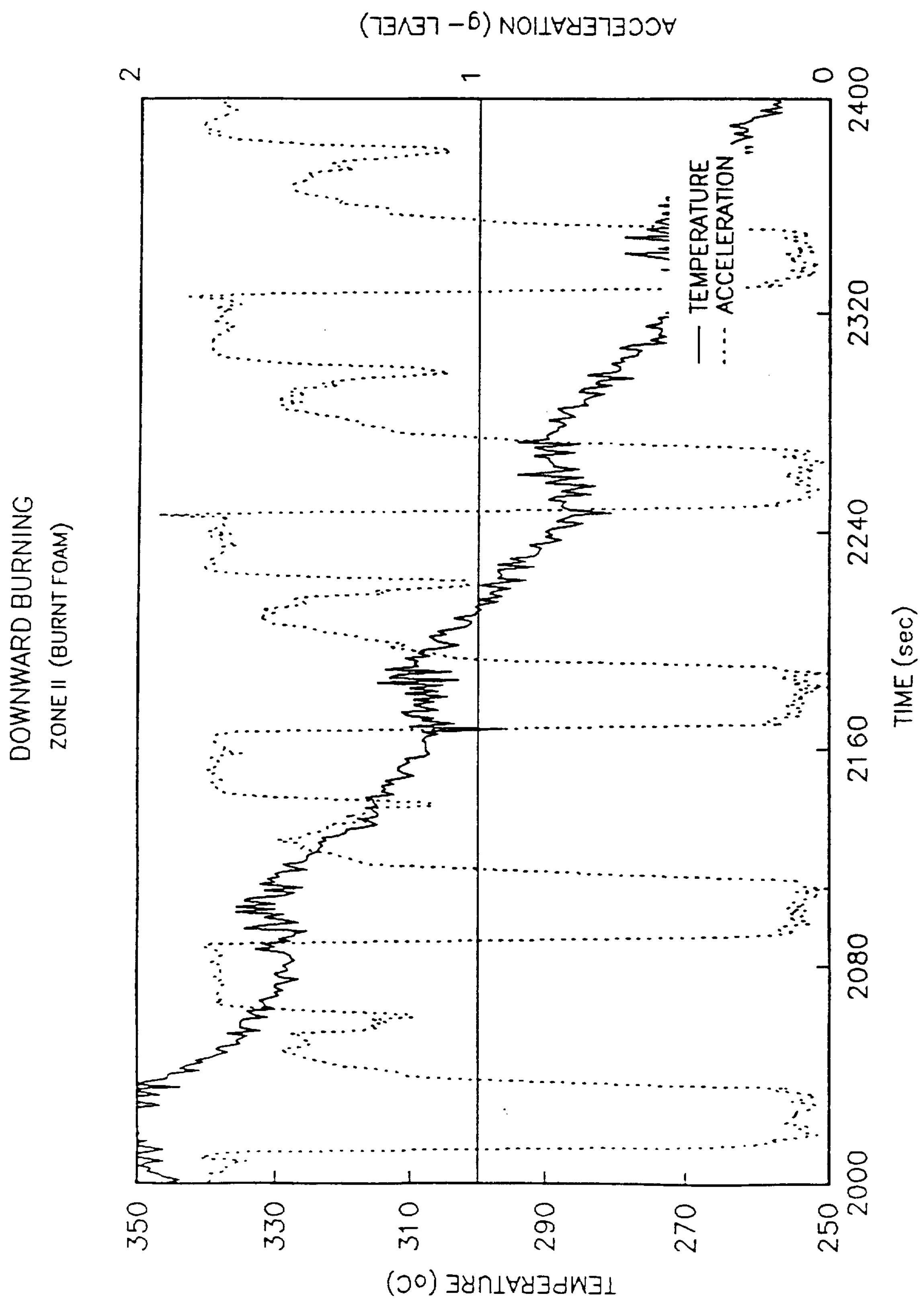

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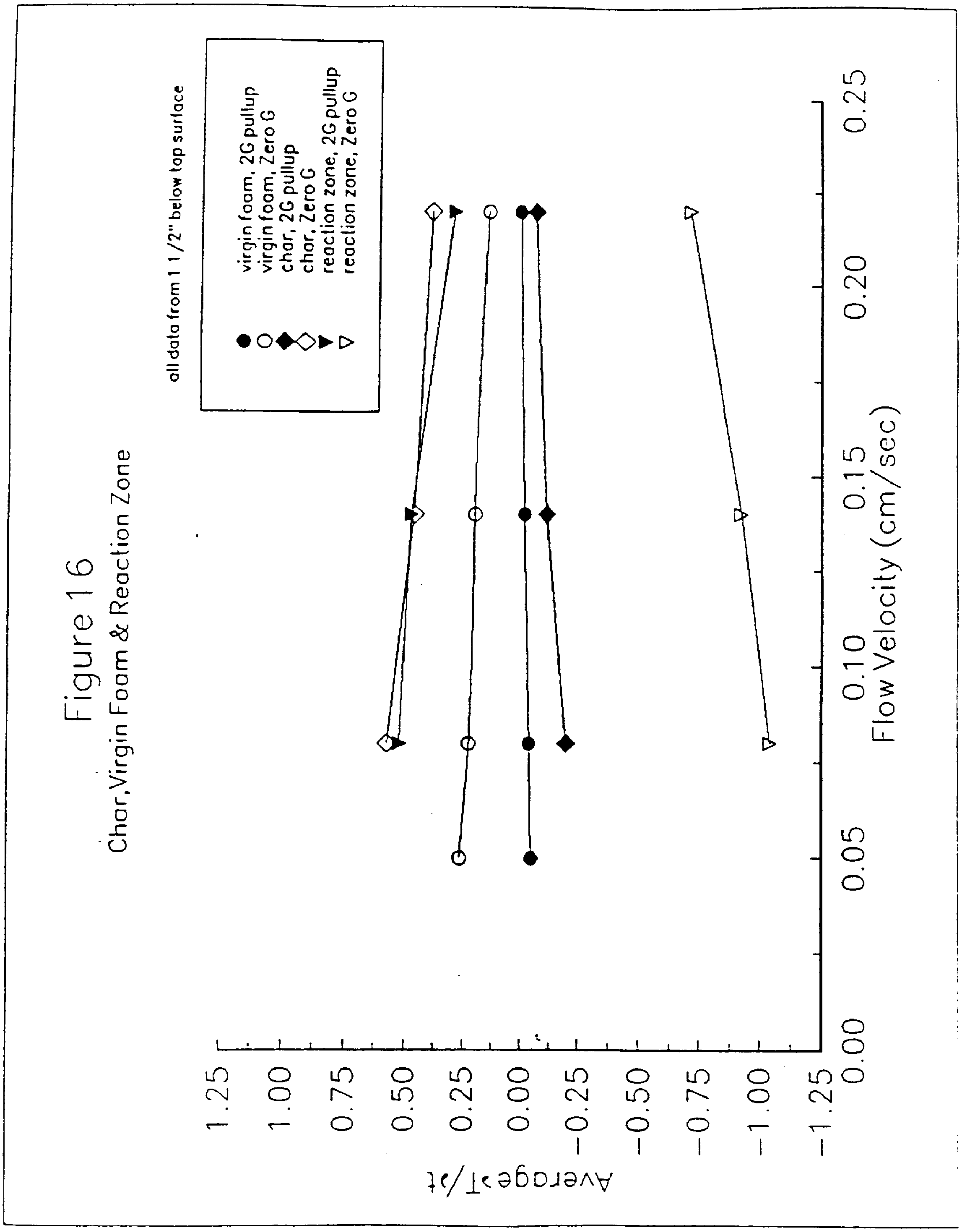
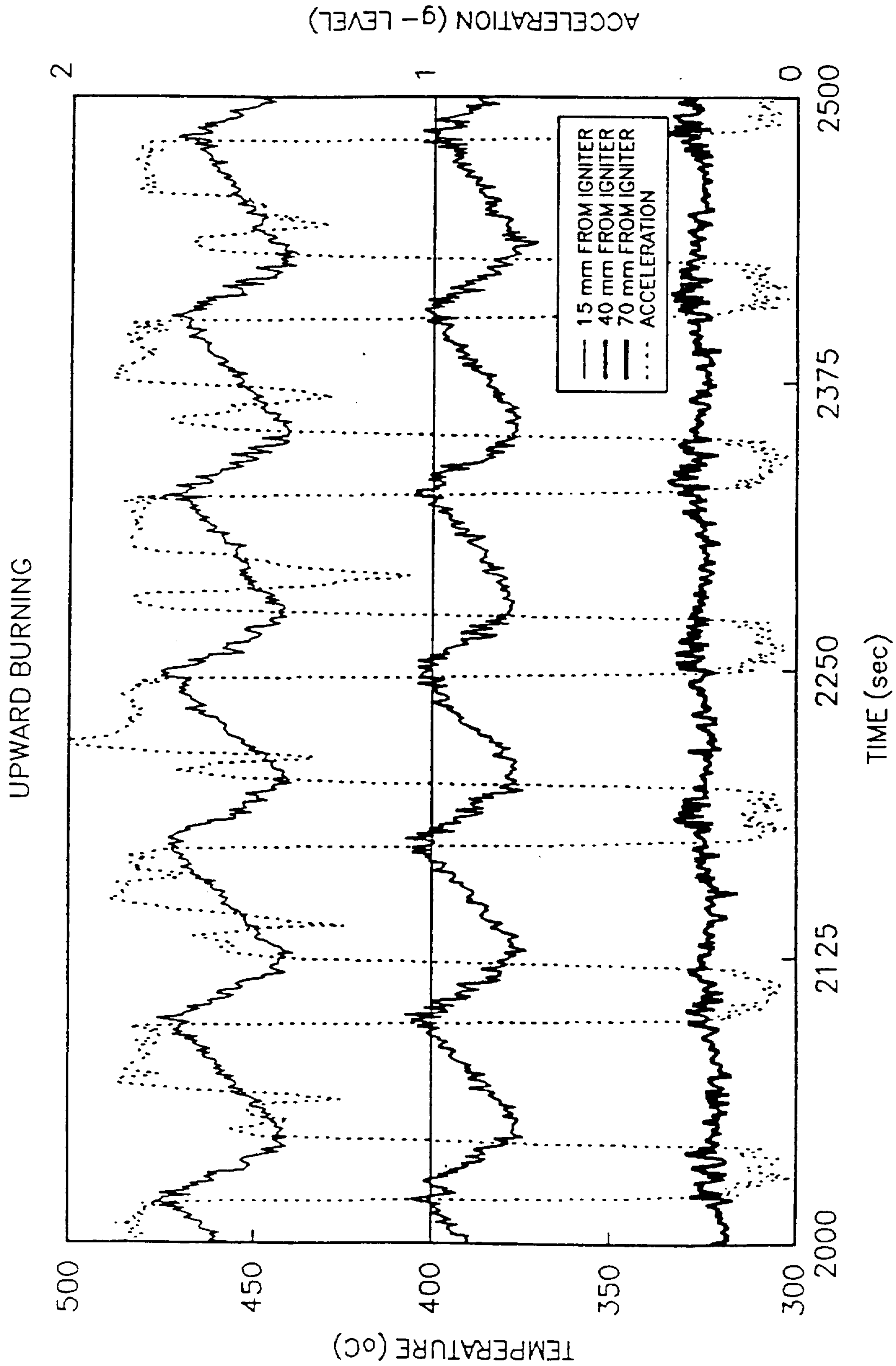


Figure 16
Char, Virgin Foam & Reaction Zone



C. Fernandez-Pello, UC Berkeley

FLIGHT HARDWARE REQUIREMENTS FOR SPACECRAFT FIRE SAFETY INVESTIGATIONS:

CURRENT STATUS AND FUTURE REQUIREMENTS

M. VEDHA-NAYAGAM
Wyle Laboratories
Huntsville, Al 35758

Workshop on Spacecraft Fire Safety
UCLA
October 31 - November 1, 1991

OUTLINE

- SCIENCE AND ENGINEERING REQUIREMENTS FOR SPACE CRAFT FIRE SAFETY EXPERIMENTS
- CONSTRAINTS ON EXPERIMENTAL HARDWARE
- CURRENT STATUS OF MICROGRAVITY COMBUSTION EXPERIMENTAL HARDWARE
- FUTURE NEEDS
- CONCLUSIONS

SCIENCE AND ENGINEERING REQUIREMENTS

REQUIREMENTS STEMMING FROM A STRATEGY TO MINIMIZE FIRE RISK ONBOARD A SPACECRAFT

BEFORE FIRE →	FIRE INITIATION →	FIRE SPREAD →	DETECTION SUPPRESSION →	CLEANUP
Material Screening /selection	Ignition	Spread Rates - Solids	Detectors	Toxicity
Environment Selection	Radiation Heating	- Gas Mixtures	Transport /Losses	corrosion
Configuration Control	Heat Loss	Smoldering	Fire Signatures	etc.
Fire Retardant Materials	Geometry	Burning Rates	Supp. Effectiveness	
		Gravity Jitter	Dispersion	
		Flow Field	Artificial Intelligence	
		Smoke Spread		
		Other		

OVERALL FIRE DEVELOPMENT SCENARIO

M. Vedha-Nayagam, WYLE Laboratories

SCIENCE AND ENGINEERING REQUIREMENTS

EXAMPLES

- CORRELATION BETWEEN GROUND BASED TEST METHODS AND MICROGRAVITY ENVIRONMENT (NHB 8060.1C)
- MATERIAL END-USE CONFIGURATION AND ITS EFFECT ON FLAMMABILITY CHARACTERISTICS
- EXTINGUISHANT EFFECTIVENESS IN MICROGRAVITY ENVIRONMENT

M. Vedha-Nayagam, WYLE Laboratories

CONSTRAINTS ON EXPERIMENTAL HARDWARE

- CARRIER ACCOMMODATIONS
  - Size
  - Power
  - Heat Rejection
  - Exhaust
  - Data Acquisition
- CARRIER SAFETY RESTRICTIONS
  - Containment
  - Toxic Release
- OTHER
  - Environment
  - Accessibility, Degree of Automation
  - Scheduling, etc.

LOW-GRAVITY COMBUSTION EXPERIMENTS HARDWARE

- SOLID SURFACE COMBUSTION EXPERIMENT (SSCE)

Specifications

Volume = 0.04 m^3

Max. Pressure = 160 kPa

Measurements

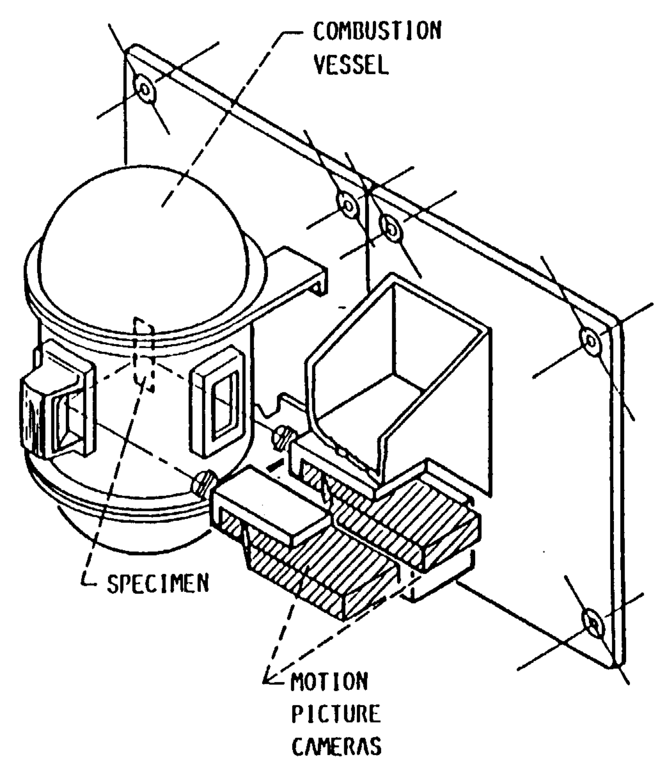
Two High Speed Cameras

Solid and Gas phase Thermocouples

Single Experiment per Container

Shuttle Middeck

SOLID SURFACE COMBUSTION EXPERIMENT (1990)



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LOW-GRAVITY COMBUSTION EXPERIMENT HARDWARE

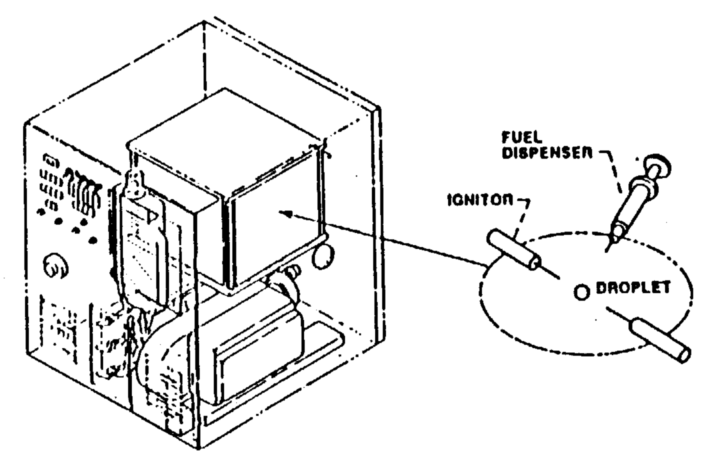
- DROPLET COMBUSTION EXPERIMENT (DSE)

Specifications

Volume = 1.2 liters

Pressure 10 to 200 kPa

Max. Energy Release
4.6kcal



Measurements

Motion Picture

Still Photography

Multiple Experiments

Shuttle Middeck

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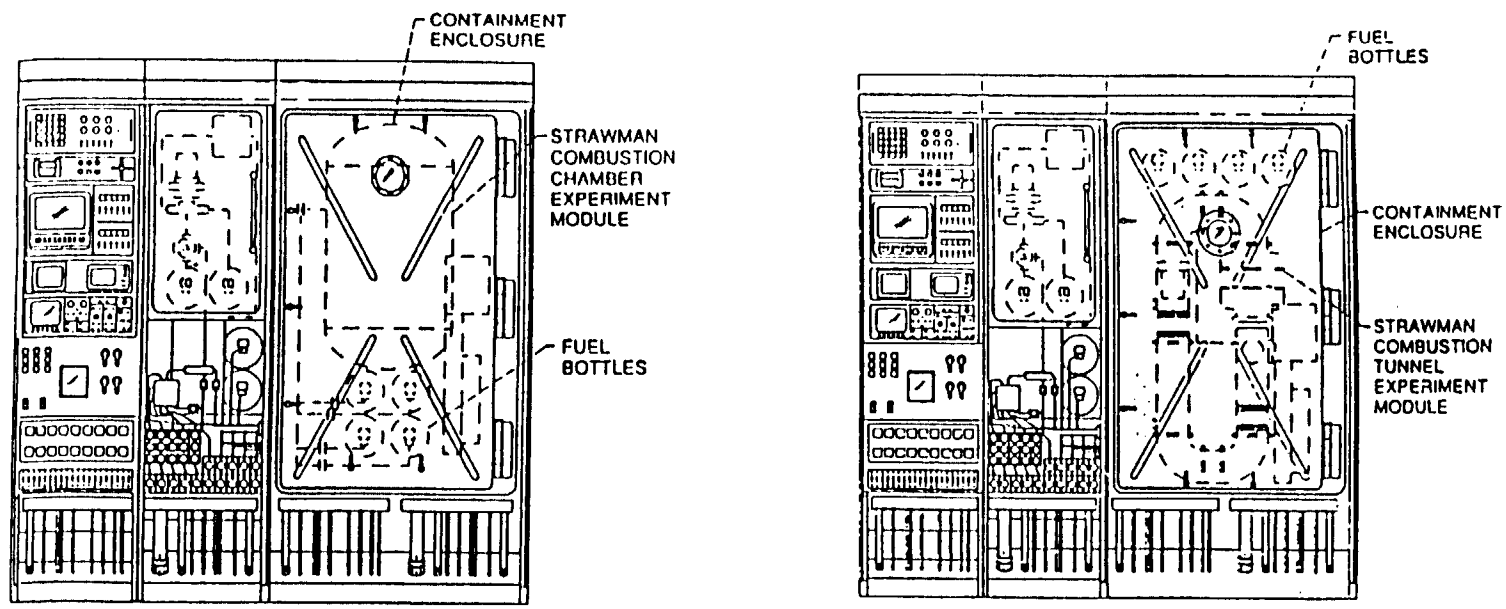
FUTURE LOW-GRAVITY COMBUSTION EXPERIMENTS HARDWARE

MODULAR COMBUSTION FACILITY



MCF ASSESSMENT WORKSHOP: MAY 17, 1989, NASA LeRC.

M. Vedha-Nayagam, WYLE Laboratories

CONCLUSIONS

- SPACECRAFT FIRE SAFETY IS MUTI-FACETED. THE EMPHASIS MUST BE FOCUSED BASED ON RISK MINIMIZATION.

- BE AWARE OF THE CONSTRAINTS INVOLVED IN MICROGRAVITY EXPERIMENTS (DURING EARLY STAGES OF EXP. DEVELOPMENT).

- MAXIMUM POSSIBLE INFORMATION MUST BE OBTAINED FROM EACH EXPERIMENT.

ha-Nayagam, WYLE Laboratories

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1992

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Findings of a Review of Spacecraft Fire Safety Needs

5. FUNDING NUMBERS
WU-506-48-4C
NAS3-25975

6. AUTHOR(S)
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University of California
Mechanical, Aerospace, and Nuclear Engineering Dept.
Los Angeles, California 90024-1597

8. PERFORMING ORGANIZATION REPORT NUMBER
UCLA ENG 92-19

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-189181

11. SUPPLEMENTARY NOTES
Project Manager, Robert Friedman, Space Experiments Division, NASA Lewis Research Center, (216) 433-5697.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 18

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The review was a workshop to guide UCLA and NASA investigators on the state of knowledge and perceived needs in spacecraft fire safety and its risk management, for an introduction to an analytical and experimental project in this field. The report summarizes the workshop discussions and includes the visual aids used in the presentations. Probabilistic Safety Assessment (PSA) methods, which are currently not used, would be of great value to the designs and operation of future human-crew spacecraft. Key points in the discussions were the importance of understanding and testing smoldering as a likely fire scenario in space and the need for smoke damage modeling, since many fire-risk models ignore this mechanism and consider only heat damage.

14. SUBJECT TERMS
Combustion; Fire prevention; Hazard; Risk; Space stations, Spacecraft environments; Weightlessness

15. NUMBER OF PAGES
206

16. PRICE CODE
A10

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135